VISUAL SEARCH STRATEGY AND INTERCEPTION ACCURACY

BY

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DISSERTATION

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ABSTRACT

Interceptive projectile aiming to a moving target such as passing in American football requires a coordinated movement sequence based on accurately perceived and/or predicted object motion characteristics. I addressed the questions of how visual search strategy and interception accuracy are influenced by constraints. Two experiments, manipulating spatial and temporal target motion configuration, assessed the role of constraints in interceptive aiming in interception accuracy and gaze control strategy.

In Experiment 1, there was an influence of constraints imposed on target speed and interception location on gaze control strategy as well as spatial and temporal accuracy of performance. With changes in target speed, the interdependent relationship between spatial and temporal accuracy was observed. Constraining the point of interception resulted in increased spatial and timing error in hitting the moving target but spatial variability of the interception point in laboratory space was independent of the interception point constraint. The greater tendency to gaze at the intended interception point, induced by the presence of a specified interception point, indicates that direct tracking of the target may not be optimal in tasks where the movement execution time and flight time are relatively long.

In Experiment 2, gaze control and interception accuracy was examined under known and repeated target speed presentation and compared to unknown and random presentation conditions. Target speed and spatial path were also varied from highly predictable to less predictable patterns. Spatial and temporal accuracy were inversely related to each other. Variation in aimed location in laboratory space was significantly influenced by target motion predictability, but not influenced by target speed. Point of gaze data also indicated that participants tended to track the moving target more, rather than look at the anticipated interception location, as target motion became less predictable.

Overall, the task constraints employed in present experiments showed a significant association with point of gaze distribution. However, the results also highlight the importance of considering the task context with the functional role of the eye. As a result, a task specific interception strategy may be required, so that the eye, head, and effector maybe coordinated to both optimize perceptual resources as well as facilitate accurate object interception.

TABLE OF CONTENTS

LIST OF FIGURES

v

LIST OF TABLES

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INTRODUCTION

Target interception requires that two objects in motion coincide at the same place at precisely the same time. To accomplish the interception successfully, one should perceive first the motion characteristics of the moving object such as the object's speed and direction, and then anticipate when the object will be at the desired interception location (i.e., perceptual anticipation, Poulton, 1952). For the control of movement, the correct response needs to be organized, initiated at the right time (i.e., receptor anticipation, Poulton, 1952), and then executed accurately with a high level of coordination between the effector and the target object in the environment. Therefore, the quality of the interception performance is dependent upon a tight cooperation between the performer's perceptual and motor processes (e.g., Turvey, 1990).

Views on Visual Search Strategy

The perceptual process of picking up and using visual information plays a critical role in determining the quality of interception performance. Because the eye is the single sensory organ that receives visual information of the environment, the nature of the information delivered varies according to the spatial and temporal regulation of gaze. From an information-processing perspective, the complex decision making process starts with determining where to gaze to capture the most important features in the environmental display (e.g., cue identification) (Tenenbaum, 2003). This process, termed "visual search strategy", specifies how eye movements are organized to search the display or scene for relevant information to guide action (e.g., Henderson, 2003; Yarbus, 1967). In interceptive timing tasks, for example, successful performance mandates that the performer attend to cues related to the speed and direction of the moving target. The visual system must act to pick-up this information at the same time that the interceptive aiming movement is being organized and executed. The visual search strategy

1

represented by the eye fixation sequence provides information regarding what, where, and potentially how much information is being processed (Abernethy, 1988). As such, eye movements are planned into the motor pattern and typically lead each action by establishing the spatial layout of the environment and checking continuously whether a particular condition is met for the execution of the action (e.g., Land & Hayhoe, 2001; Prablanc, Echallier, Jeannerod, & Komilis, 1979).

Theories in visual perception contrast how the visual system is organized and provides veridical information about the environment. Depending on whether a computational information processing framework or the direct coupling between the environment and action framework is employed, two distinct theoretical perspectives have been proposed. These theories are typically labeled as computational (or indirect) perception theory (Helmholtz, 1867; Marr, 1982) or ecological (or direct) perception theory (Gibson, 1979). From these two theoretical perspectives, predictive versus prospective hypotheses have been put forth to understand the coordination of perception and action (Abernethy & Burgess-Limerick, 1992; Davids, Savelsbergh, Bennett, & Van der Kamp, 2002; Williams, Davids, & Williams, 1999). However, no 'either-or' solution has been deduced and multiple mediating variables limit the generalizability of both views. For example, the role of tau in controlling action has been criticized by the potential errors in perceiving time-to-contact when an object is on a non-direct approach or has a non-constant velocity (Williams et al., 1999). In addition, the observed differences in time-to-contact judgment as a function of an individual's developmental age, gender, and expertise make identification of how time-to-contact information is detected more complicated (Abernethy & Burgess-Limerick, 1992).

The traditional cognitive perspective in visual search behavior underscores the role of

selective attention (Neisser, 1967). From this perspective selective attention mediates the visual search process by continuously and selectively guiding the passage of information (Duncan, 1984). The cognitive perspective presumes that visual saliency as well as acquired knowledge by experience contributes significantly to the control of eye movement location and fixation duration. Eye movement location or "point of gaze" provides information regarding the area or features of interest while the fixation duration indicates the complexity or importance of the information. However, the relationship between fixation characteristics and information processing, and thus the viability of the cognitive interpretation of visual search behavior, has been challenged due to limitations such as the covert shift of attention without eye movements, the ambiguous distinction between "looking" and "seeing", and the potential use of peripheral visual information (Abernethy, 1988).

Whole body action and eye movement control are similar in that both need to be flexible in order to adapt to variations in task conditions. The motor system attempts to find the unique solution from redundant ways to achieve the goal. The control of eye movement has been viewed as a reflection of the complex cognitive and attentional process necessary to obtain essential visual information for accurate performance. Alternatively it has been proposed that the visual search process should be consistent with ecological accounts of the relation between organisms and their environment (Williams, Janelle, & Davids, 2004). By either a cognitive or ecological account, visual search strategy as well as coordination of movement is predominantly determined by constraints. To better understand how humans assemble interceptive actions, a constraint-based interpretation of visual search behavior is worthy of further empirical investigation. By understanding the process of how visual search patterns reflect those constraints, the theoretical and practical knowledge in motor performance will be enriched (Higgins, 1977; Williams et al.,

2004).

In spite of the significant literature describing the close interaction between visual search patterns and constraints, in order to sustain the viability of a constraints-based explanation for visual search behavior more research needs to be conducted to identify the parameters that cause the different states of stability in the visual system (Williams et al., 2004). Borrowing concepts from dynamical systems theory, stable states of behavior emerge from a self-organization process in which a particular control parameter determines the stable states of organization (e.g., phase transition from walking to jogging as locomotion speed increases). Applying these ideas to the visual system, Williams et al. (2004) argued that the visual system can be viewed as a complex system with redundant degrees of freedom where the system has multiple states of stability (e.g., Bernstein, 1967). In this view, the emergent search pattern results from the unique constraints of the task. That is, key constraints acting on a system at any given moment lead the performer to achieve the task goal by stabilizing the visual system to the coordinated state. The specified status of information-movement coupling allows the performer to organize actions by facilitating the processes of programming or self-regulation. The process to excavate the nature of parameters controlling the visual search pattern could be enhanced by experimentally manipulating the potential parameters within Newell's (1986) framework of constraints on motor behavior.

To attain the state of stability, the visual system needs to limit the possible combinations of parameters associated with the perceptual process. A variety of parameters are potentially available including the extent to which information is sampled through the fovea, parafovea, and visual periphery and the manner in which performers use different types of eye movements such as saccades and pursuit tracking (Fitch, Tuller, & Turvey, 1982; Williams et al., 2004).

Constraints imposed on the task function as inhibiting or facilitating the potential for flexibility inherent within the visual search strategy. As such, the visual search pattern is not only a reflection of a cognitive top-down process operated by acquired knowledge and visual saliency, but also needs to be viewed as the process interacting with imposed constraints in order to optimize the perceptual source of information. This dissertation is designed to provide a greater understanding of the guidance of interceptive action and, more specifically, the role played by constraints in visual search strategy in interceptive action.

Visual Search Strategy in Object Interception

Object interception requires that the performer perceives the motion characteristics of the moving object and generates an interception movement tuned to both the moving target and the space and time requirement of the task. The visual search process attempts to coordinate the eye's point of gaze with information rich areas in the environment. As the object moves through space the area in the environment that is most information rich changes. Adapting the point of gaze is complicated by a number of time delays in the visuomotor system. These delays include intrinsic sensorimotor delays, the latency for the initiation of eye movement (Maunsell & van Essen, 1983), and the time to estimate key parameters of a visual motion signal (Mrotek, Flanders, & Soechting, 2004). In order to compensate for these delays, anticipation processes must be incorporated to estimate the arrival time of the target stimulus (e.g., perceptual anticipation). Similarly, anticipatory processes must also be incorporated into response organization (e.g., receptor anticipation) (Poulton, 1952, 1957). For example, in attempting to hit a baseball the hitter looks at the central body parts of the pitcher during the wind-up and then shifts the point of gaze to the area of ball release (e.g., McRobert, Williams, Ward, & Eccles, 2009). After ball release pursuit eye movements follow ball until the point of gaze shifts to the

5

ball-bat contact point (Land & McLeod, 2000). Each of these shifts in point of gaze requires anticipation based on predicted ball speed and ball spatial location.

The visual information required to optimize task performance and the associated visual search strategy is determined by constraints. Constraints imposed on acquiring visual information for interceptive actions are related to the environment, the object or surface, and the limb and/or implement used to intercept the target. Constraints-based interpretations imply the existence of different control mechanisms for successful completion of different types of tasks (e.g., Davids et al., 2002; Seth & Edelman, 2004). Constraints employed in previous visual search studies have been somewhat narrow. In many experiments none of the targets were moving (Behan & Wilson, 2008; Vickers, 1992, 1996; Vickers, Rodrigues, & Edworthy, 2000; Vickers & Williams, 2007; Williams, Singer, & Frehlich, 2002), so that the perception-action process could be regulated with a self-paced tempo. For externally-paced tasks, the direction of target motion has been largely limited to a head-on approach and thus the interceptive actions employed were constrained mostly to catching (Panchuk & Vickers, 2006, 2009), hitting (Bahill & LaRitz, 1984; Land & McLeod, 2000; McKinney, Chajka, & Hayhoe, 2008; Rodrigues, Vickers, & Williams, 2002), or receiving (Vickers & Adolphe, 1997). Moreover, the above studies have emphasized skill-based differences (e.g., expert vs. novice) in describing the significance of parameters manipulated (e.g., accuracy achieved, task complexity, type of display, or anxiety level). Consequently, the application of those findings to different task, environment and organism constraints seems premature.

Vickers (2007) proposed a gaze control framework which has at its foundation a constraints-led model of motor coordination (e.g., Newell, 1986; Williams et al., 2004). The diverse characteristics of the task result in visual search patterns that do not have one

6

consolidated pattern, but instead the pattern varies to meet the diverse task demands. Three main categories of tasks: targeting tasks, interceptive timing tasks, and tactical tasks were classified. The targeting task, in which the interceptive aiming task belongs, was classified into sub-categories based on whether the target is in motion and how many critical spatial locations and cues are important to the visuomotor system. Consistent with Vickers' model, the series of saccades that anticipates the location of the object in motion have been shown to depend on the spatial and temporal configurations of the target motion (Causer, Bennett, Holmes, Janelle, & Williams, 2010; Panchuk & Vickers, 2009).

While visual control strategies are well understood for stationary target aiming, much less is known regarding coincidence timing and interceptive aiming. For example, in coincidence timing tasks neither foveal information of the moving target nor visual search may be required for accurate performance (Long & Vogel, 1998; Peterken, Brown, & Bowman, 1991). In interceptive hitting detailed foveal vision may also not be required (Mann, Ho, de Souza, Watson, & Taylor, 2007). Task accuracy requires the acquisition of stable perceptual coordinates in space by anchoring the eye and head to the predicted direction of ball-bat contact (Lafont, 2008; Rodrigues et al., 2002). Neither continuously anticipating the target motion with saccades nor foveating the target location/object longer was the determinant of interceptive hitting performance. Different visual control strategies for stationary target aiming, coincidence timing, and interceptive hitting indicates that gaze control is flexibly adapted to the task demands. For interceptive hitting, anchoring the head and eye to the predicted point of ball-bat contact allows the performer to pay more attention to the high-priority component in response organization, that is, the ball-bat contact (Rosenbaum, 2010). The focus on response organization rather than on ball tracking is acceptable as long as the quality of motion perception is not degraded.

In summary, how sensory information is picked-up, processed and organized into movement responses needs to be investigated together with constraints. In this dissertation, I examine visual search strategy and response accuracy in far target interception and demonstrate how gaze control strategy is mediated by the specific task conditions. Specifically, participants will attempt to intercept a horizontally moving target by projecting an object so that the target and object collide. Characteristics of target motion and interception location will be manipulated. It is expected that the visual search strategy and response accuracy will vary depending on the specific task and environment constraints employed.

LITERATURE REVIEW

"The greatest crime a passer can commit is to have a pass intercepted" (Frala, 2007, p. 57). This statement stresses that the quarterback in American football needs to put the accuracy of passing on the priority order, rather than the ability of fast and long distance throwing. Besides the interceptive skills in sports such as catching a fly ball, hitting a baseball, or stroking a tennis ball, there are numerous tasks in daily life that are performed by matching spatial and temporal requirements. In performing interceptive actions, being at the right space at the right time is critical, and without the guidance of vision interception may not be performed successfully. Issues pertinent to the study of interceptive action include, theories in visual perception and control of interceptive action, factors affecting timing judgment in coincidence anticipation, characteristics of the oculomotor system and its function in interception skill, and the role of constraints in visual search strategy and action. Due to the wide scope of interceptive actions, this review will be focused on the interceptive actions performed manually.

Theoretical Approaches to Visual Perception

A successful interception requires the effector to be placed at the destination of the moving target at the time of target arrival. The spatial-temporal coincidence between the effector and the target is critical. The estimation of object motion in three-dimensional (3D) space is fundamental in synchronizing the effector movement with sensory cues associated with target motion. The estimation process starts from the optical target image constructed on the retina, which is two-dimensional (2D). This issue, which is called the inverse problem of vision (Palmer, 1999), does not have a unique solution because the objects' images on the retina are viewed differently depending on the point of view, distance, and illumination, etc. Thus, a possible solution for these unspecified problems can be addressed by taking advantage of

9

environmental regularities (Zago, McIntyre, Senot, & Lacquaniti, 2009). Currently, two historical perspectives have been contrasted for the problem of visuo-motor coordination in interception: the ecological theory and the constructivist theory.

Constructivism

The constructivist approach is the older, more "classical", approach. It has also been called indirect, Helmholtzian, cognitive, algorithmic, and meditational perception theory (Norman, 2002). Visual information in constructivist theory is considered to be insufficient so there must be some additional source of information beyond the retinal image that is used in the process of seeing (Palmer, 1999). From this view sensory receptors are provided with impoverished inputs, and in order to drive meaning from the sensory input, construction of an internal representation of the object is necessary to predict the object's motion and to guide the action toward it. Helmholtz (1867) proposed that perception depends on a process of "unconscious inference". What this means is that vision requires a process of "inference" to bridge the gap between the optical information available from retinal stimulation and the perceptual knowledge derived.

In the constructivist approach, to extract meaning from the information on the retina, perception involves a series of meditational procedures. The processes focus on the computational stages, types of representations, and storage requirements in visual information processing. Three different levels of analysis are considered in computational vision theory: computational, algorithmic, and implementational level (Marr, 1982) (as cited in Abernethy & Burgess-Limerick, 1992, p. 352). First, at the computational level, the specific task information needs to be identified with the raw informational source. Second, at the algorithmic level, the detailed algorithmic mechanism for processing the optical source of information should be

prepared and tested. Lastly, at the implementational level, examination of the neural pathway to enable the algorithms to work is of interest. So, the indirect perception approach explains the perception of dynamic visual information as a series of processes that capture the static retinal image and improve it to provide a reliable depiction of the environment (Abernethy & Burgess-Limerick, 1992).

As such, the constructivist approach does not focus on the information on the retina itself, but rather on the meaning extracted from the information. That is, the constructivism considers that perception is separate from action. Thus, when one produces a motor response in a perceptuo-motor task (e.g., interception task), the action is preceded by the sense of information and the process of that information (Ranganathan, 2005).

Ecological Theory

In contrast to constructivism, ecological theory rooted in Gibson's ecological optics (1979) in which perception is understood by analyzing the structure of the organism's environment, called ecology. Ecological theory has also been called direct, Gibsonian, sensory, proximal, and immediate perception theory (Norman, 2002). This newer theory is about the informational basis of perception in the environment rather than about its mechanistic basis in the brain (Palmer, 1999). Gibson hypothesized that in normal (ecological) conditions the information available in the stimulus is sufficient for adequate perception of the environment. In addition, the information is 'out there' ready to be perceived as something very much like the radio receiver which does not have to compute it. So, the term "invariants" was developed as the sources of information in the stimulus to which the perceptual systems are tuned. Three hypotheses were proposed by Gibson: the stimulus is informatively sufficient in ecological conditions, information is carried by invariants which are specified by environmental properties,

and invariants are detected directly (Tresilian, 1999).

The concept of ecological optics considers perception as the active exploration of the environment. When the observer moves in the world, the spatial pattern of stimulation on the retina constantly changes over time. Gibson developed the term, "optic flow", and it is explained by the concept that changes in head position induces the changes in the angles of light rays entering eye and it particularizes the distinct types of movements with respect to the environment. So, the spatiotemporal information as well as the identification of objects and events could be achieved by this process. Lee (1980) demonstrated the concept of TTC (time to contact), by mathematically calculating the temporal prediction about when the object will arrive. The term 'tau', the optical information specified on the retina about the remaining TTC between the point of observation and an approaching object, was developed and used to denote the TTC. Lee argued that tau is proportional to the reciprocal of the rate of expansion of the object's image on the retina and it plays a role in triggering the action without internal processing (Lee, 1980).

Another important concept discussed by Gibson was "affordances". Gibson believed that because sensory stimuli are derived from organism-environment interaction ("affordances") and the environment exists only in perceivable units. Hence people perceive the affordances of the objects rather than the properties of the object itself. For example, in soccer, players do not perceive the ball in terms of its physical dimensions, speed, or distance away, but in terms of its affordances for action such as whether the ball can be headed, trapped, or dribbled. Thus, a single object may produce various affordances. Compared to the constructivism's, focus on the processes in perception, the ecological approach concentrates on the information arriving at the retina. It is believed that movements are directly controlled by information in the optic array and

in turn the subsequent movements produce a corresponding change in the optic array. This cyclic relationship between perception and action is a unique feature of the ecological approach. In addition, the concept of affordances provides a meaningful way of combining perception and action. The important implication for sport and exercise science research is that perception can only be studied in experiments where perception and action are coupled together (Williams et al., 1999).

The problem of circularity between perception and action in ecological optics, however, has led to theory revision. The necessity to account for the role of extra-retinal information and central processing of visual information led to a different approach in studying the control of interceptive actions (Zago et al., 2009). Tresilian (1994a, 1994b, 1999), for instance, examined not only what perceptual invariants lead the action (e.g., tau and image size) but also how those invariants control the movement kinematics. He also criticizes the general notion that tau provides time to contact information and controls interceptive actions (Bootsma & van Wieringen, 1990; Savelsbergh, Whiting, & Bootsma, 1991). Hence, it has been argued that the ecological approach needs to incorporate the issues of how other sources of information can specify actions and act as constraints on human movement (Williams et al., 1999).

Two Visual Streams

The classic view of perception, constructivism, assumes that mental representations provide not only the underpinnings for visual cognition, but also the visual configurations demanded for action. Based on accumulated neuropsychological, electrophysiological and behavioral evidence, however, Goodale and Milner (1992) proposed that the neural substrates of visual perception may be quite distinct from those underlying the visual control of actions. The two-visual system hypothesis originated, in fact, from lesion studies providing evidence of a

difference between the function of the visual areas in the temporal versus parietal lobes of the

Table 1 *Summary of the two systems (summarized from Norman, 2002)*

Characteristic	Ventral System	Dorsal System
Function	Recognition and identification Size perception	Allow visually guided behavior Identification of moving objects
Sensitivity	Sensitive to high spatial frequencies Seeing fine details	Sensitive to high temporal frequencies Seeing motion
Memory	Memory-based system	Short-term storage
Speed	Slow (parvocellular and magnocellular input)	Fast (magnocellular input)
Consciousness	More conscious	Less conscious
Frame of reference	Allocentric (Object-centered information, Relative metrics)	Egocentric (Absolute metrics)
Visual input	Foveal and parafoveal visual input Less affected by monocular vision	Less affected by retinal eccentricity Affected when vision is monocular

monkey's cortex (see Table 1). Two pathways were identified; the inferior temporal centers in the

lower (ventral) system and the parietal centers in the upper (dorsal) system. These systems are

called the "what" system and "where" system due to the functional involvement in identifying

and locating objects, respectively (Ungerleider & Mishkin, 1982). In accordance with Gibson's

ecological perception, Neisser (1989) assumed that the "what" system underlies recognition and

categorization which require the internal representations of categories in memory and the

"where" system is for direct perception.

Re-interpretation of this view by Milner and Goodale (1995) more clearly addressed the differences in function between the two streams. As can be seen in Table 1, the key contribution of the perceptual mechanism in the ventral stream is the identification of possible and actual goal objects and the selection of an appropriate course of action to deal with those objects. On the other hand, the dorsal system is a parallel visual system to program and control well-practiced visually guided tasks by using current visual information about an object in real- time. Thus, the dorsal stream, which is a vision for action, is not normally engaged unless the target object is visible during the programming phase (Milner & Goodale, 2008). That is, both streams contribute to action, but in quite different ways.

Theoretical Approaches to Action

The two main traditional views of looking at coordination and control of actions were central and peripheral control. The distinction between these two comes from whether movements are controlled by feedback or by central representations. James' (1890) response-chaining hypothesis was the precursory theory recognizing the value of sensory information in movement. It held that coordinated motor output is composed of smaller, discrete phase of movement, linked together by a "chain reflex".

Sensory feedback from each phase reflexly initiates each subsequent movement in turn (Kelso & Stelmach, 1976). Early deafferentation studies of Sherrington (1906) supports the peripheral control hypothesis because eliminating feedback by severing the dorsal root of a monkey resulted in elimination of movement altogether. However, follow-up deafferentation studies (Lashley, 1917; Taub & Berman, 1968) draw the conclusion that feedback from the moving limb is not essential for movement to occur, but critical to assists the movement to be

15

controlled accurately. Thus, an alternative mechanism of motor control emerged, where the role of sensory processes is more or less reduced in prominence. Central control theory assumed that the higher center of CNS already processes the necessary information to control movement so that the feedback based control of movement is redundant and thus is not necessary. These two control theories are followed by the closed- and open-loop control theory, respectively.

Adams (1971) developed a closed-loop theory of motor skill learning and control and two memory states were suggested in order for the system to have the capacity to detect and correct its own errors. In his theory, the movement is selected and initiated by the memory trace and is controlled by the perceptual trace. The memory trace is a modest motor program that only selects and initiates the response rather than controlling a longer sequence. The perceptual trace, on the other hand, governs movement extent by receiving feedback and comparing the current movement to the memory representation of the goal movement. Because the closed-loop theory had a heavy concentration on the latter, perceptual trace, a lack of emphasis on open-loop control processes existed.

Schmidt (1975) proposed the schema theory as an alternative of Adams' theory. The closed-loop theory had some strength in that it considers the learning of novel motor task in addition to the performance of already-acquired skills, it is relatively simple to account for the learning of positioning tasks, and it is empirically supported either directly from motor behavior or indirectly inferred from other response classes. Because there were some criticism about the amount of information that must be stored in CNS and about how the performer produces a "novel" movement, the schema theory put considerable emphasis on the role of generalized motor programs. Schmidt (1975) defined a schema as a rule or set of rules that serves to provide a basis for a movement decision. Whenever the individual produces a movement, four sources of

16

information: the initial conditions, response specifications, sensory consequences, and response outcome, are stored and incorporated into the schema which becomes stronger with repetitions or various experiences. Two types of schema, recall schema and recognition schema which corresponds with memory and perceptual trace in Adam's closed-loop theory, respectively, were conceptualized. So, when the individual encounters a novel condition, the required movement is generalized using the general rule based on the invariant features and four parameters mentioned above.

Predictive versus Prospective Control

In line with closed-loop and schema movement control theories, the predictive control and the prospective control theories (Chapman, 1968; McLeod, 1987) were proposed to describe the control mechanisms in interceptive action. The information processing paradigm was used to describe the processes of perception and movement control in interceptive actions, indeed, for the reason that it includes the notion of central intermittency, the perceptual moment hypothesis, and the serial processing idea of the single channel hypothesis. Williams et al. (1999) and Poulton (1950, 1952) proposed two types of information sources as a reflection of information processing paradigm in explaining the organization of interceptive action. Two types of anticipation process, receptor anticipation and perceptual anticipation, were emphasized for accurate interceptions to be made. Receptor anticipation, which provides a reference to predictive control, exists when stimulus events are displayed ahead, so that the performer can preview the approaching event and respond without the lag due to reaction time. On the other hand, perceptual anticipation, which is a source of information in prospective control, may be found in situations where no preview is given but the presentation of the stimuli is regular in some way and thus can be learned by the performer (Schmidt, 1968). In the latter type of

anticipation, at least two classes of perceptual anticipation are to be evaluated: spatial anticipation (e.g., direction or extent) and temporal anticipation.

A typical situation where predictive control is necessary is when the short duration of a task makes any modification of the movement impossible, so that the parameters of the movement such as the onset, duration and extent of the movement must be predetermined. This advanced movement planning reduces the influence of the delays due to the neural and neuromuscular transmission. The estimation of future target position at interception can only be predicted by the brain via extrapolation of the current estimate of the position, speed and acceleration of the moving target. Those estimates may be measured by the visual system (e.g., optical tau), so that the accuracy (mean error) and precision (error variability) of the prediction are influenced by the visual estimates of target motion. Because predictive control assumes that the motor response is initiated after a visual or internalized variable has reached a critical value (Zago et al., 2009), prediction errors will be smaller if the prediction is updated at the last possible moment. So the more experiences in interceptive situations might enhance the internal computational algorithm of the action to be efficient.

In prospective control, where the target is going (the interception point) and when it will arrive there (TTC) are not computed in advance. Instead, the motor response is controlled continuously based on online sensory feedback. That is, the brain keeps monitoring the relation between the visual information and the spatio-temporal characteristics of required movements in a continuous fashion (Chapman, 1968; McLeod, Reed, & Dienes, 2006). Thus, the time and space of interception emerges from the continuous adjustment of the movement variable (e.g., locomotor or hand velocity) as the movement progresses (Dessing, Peper, Bullock, & Beek, 2005). Prospective control provides a more detailed picture of how movements are controlled in

terms of adaptation to unexpected changes in the environment. Nevertheless, the human movement control system possesses the innate constraints of a visuo-motor delay (VMD) which is defined as the time period between the pick-up of information and its use in producing an adjustment in movement (Tresilian, 1993). Consequently, it is impossible for the movement to be adjusted immediately in response to changing information or an initial response deviation. In order to accomplish the accurate movement timing, the visuo-motor delay must be compensated. The compensation does not necessarily need to be predictive or representative, but can be made by attuning some parameters of the control law, so that the movement could be adapted to the constraints of a specific task (Benguigui, Baures, & Le Runigo, 2008). So, visuo-motor delay depends on the type of task (Bootsma & van Wieringen, 1990; Lee, Young, Reddish, Lough, & Clayton, 1983; Whiting, Gill, & Stephenson, 1970), the use of information (i.e., continuous mode or discrete mode), and the skill of the performer.

<u>Interceptive Actions</u>

Characteristics of Interceptive Actions

Stationary target aiming requires only matching movements to the spatial characteristics of the environment. That is, due to the absence of temporal constraints, the kinematic composition of the motor act leads to goal achievement only if the displacement matches the current state of the environment (Higgins & Spaeth, 1972). As the target moves continuously, however, the process of updating visual information as well as the control of movement should be managed coincident with temporal and spatial kinematic specifications. Thus, the spatial and temporal accuracy demands of interception action cause a conflict with the general notion of the speed-accuracy trade-off, in that movement times are similar when spatial accuracy is important and movement times are briefer when temporal accuracy is important (Tresilian, 2004).

19

Interceptive actions can be defined as those activities that involve relative motion between an actor and an object, implement, or projectile (Davids et al., 2002). An underlying principle is that both of the moving components have to be in the right place at the right time. The taxonomy of interceptive actions includes a wide range of motor responses (fine and gross), situations (static and dynamic environments), and tasks (discrete and continuous). Since Helson (1949) recognized first that anticipation is a factor in motor performance, anticipation in motor skills has been investigated systematically. One class of interceptive action is coincidence anticipation that requires participants to make a simple response (e.g., button press) at the same moment as a moving target arrives at a pre-defined position (Tresilian, 1995). To achieve the task goal, two main categories of anticipation processes are required: perceptual anticipation and receptor anticipation (Poulton, 1950, 1952). Perceptual anticipation represents the prediction of the time at which an object will arrive at the point of contact, based on its velocity and distance, whereas receptor anticipation indicates the prediction of the moment to initiate an action, based on knowledge about movement duration. Typically, perceptual anticipation processes are of interest in the study of perceptual aspects of skilled performance and receptor anticipation processes are of interest in the study of motor aspects of performance (Haywood, 1976). As greater spatial synchrony between the moving target and effector (e.g., hand, hand-held implement, or projectile) is required, however, the task (i.e., interception tasks) involves different coordination processes within the body parts as well as between the body and the environment.

The two classes of timing tasks above, coincidence anticipation and interception, are similar in that a series of processes should be accompanied together including motion detection, judgment on and prediction of stimulus characteristics (e.g., speed), integration of perceived information, and coordinating the information with action. These processes are influenced

20

mainly by two distinct factors, stimulus-related variables (e.g., velocity) and response-related variables (e.g., movement distance). In addition, the success of both tasks is determined primarily by the visual information, which provides the most significant information about the environment as well as the position and motion of the body with respect to the environment (Davids et al., 2002; Lee, 1976).

Interception tasks are rather dissimilar to coincidence anticipation in the sense that higher spatial synchrony is essential between the target and effector in an interception task. In general, two types of coordination processes are involved in interceptive actions. First, to achieve the goal, the performer must acquire an efficient and effective pattern of skeleton-muscular action. Second, there must be coordination between key limbs (including the whole body) and the environment (Turvey, 1990). For the second coordination, it is necessary for the target object and the effector to be at the same location (spatial coincidence) at the same time (temporal coincidence).

Although there is no general consensus concerning how interceptive timing is processed, two broad classes of timing control models have been proposed. Depending upon the extent to which the exteroceptive information (normally derived from vision) plays a role, predictive control and prospective control hypotheses were proposed (Davids et al., 2002). Each control hypothesis (i.e., predictive and prospective) appears appropriate to explain interception strategies for different types of tasks. Whereas tasks requiring the control of locomotor action such as catching a fly ball or leaping onto prey are mostly supported by the prospective control hypothesis (Chapman, 1968; Peper, Bootsma, Mestre, & Bakker, 1994) in which on-line use of visual information in locomotor guidance was implicated, time-pressed actions such as baseball batting (McLeod, 1987) appear to be consistent with the predictive hypothesis. However, even in

21

the same task, the employed strategies could be different depending on the configuration between the spatial representation of the target and the intercepting effector. Tresilian (2005) configured the manual interception tasks according to how the effector meets the moving object in terms of the moving direction (see Figure 1). For example, in pure pursuit (A) the target and the intercepting effector move along the same path in the same direction. In a perpendicular approach (D) the target and effector move along different paths and the point of interception is specified. Because movement time (MT) is increased in pure pursuit (Jagacinski, Repperger, Ward, & Moran, 1980) or decreased in perpendicular hitting (Tresilian & Houseman, 2005; Tresilian & Lonergan, 2002) as target speed increases, it was proposed that different control strategy might be applied according to the configurations of the interception scheme.

Figure 1. Simple linear approach configurations for interception (adapted from Tresilian, 2005).

Stimulus-related Factors in Interceptive Actions

While the stimulus is being presented, a performer has at least three cues: spatial, temporal, and velocity cues (Haywood, 1976). The most common paradigms used in coincidence anticipation studies have been to anticipate the time of coincidence or the prediction of the point of coincidence. Coincidence timing is affected by perceptual factors such as speed, plane, direction, and viewing duration of the moving stimulus.

Speed of the moving stimuli has been found as a major determinant of performance in coincidence anticipation. However, general consensus about the influence of speed on timing accuracy has not been drawn yet. While some studies showed that the performer was more accurate at faster speeds (Dunham & Glad, 1985; Long & Vogel, 1998; Peterken et al., 1991; Wrisberg, Hardy, & Beitel, 1982), others found the opposite results (Coker, 2005, 2006; Park, 2003; Peters, 1997). Studies showing greater temporal error at faster target speeds commonly employed a high moving stimulus speed (over 3000 mm/s) which allows a viewing time of only about .4 sec (Coker, 2005; 2006; Fleury & Bard, 1985). Speed effects on coincidence timing accuracy were varied also by the order of presentation and the knowledge of stimulus speed (Shea et al., 1981). Moreover, the same speed (e.g., 223.5 cm/s) caused different timing performance when it was included within different speed ranges (44.7, 134.1, and 223.5 cm/s vs. 223.5, 312.9, and 402.3 cm/s) (Haywood, Greenwald, & Lewis, 1981). The speed effects on coincidence timing judgment were also modified when the tasks used had different movement requirements. For example, target speed increases were associated with a decrease in temporal accuracy (Abernethy & Neal, 1999; Coker, 2006; Park, 2003) or having no effect on temporal accuracy (Fleury & Bard, 1985; Peters, 1997) when the required movement was a button-press (e.g., perceptual judgment). In contrast, temporal accuracy increased when the target was

intercepted directly by a projected object (Fleury, Basset, Bard, & Teasdale, 1998) or an effector (Tresilian & Plooy, 2006).

With respects to the plane or direction of the path of the moving stimuli, it was found that accuracy was greater when the target moves in the frontal plane rather than in the sagittal plane. It was argued that this may be due to the fewer reference points in the sagittal plane (Kuhn, 1993). However, the stimulus approaching directly from the front produced smaller temporal error compared to when the stimulus came from left or right (Payne, 1988), or approached slightly to the left or right of the midline of the body (Ridenour, 1974). This was also supported by Antoniou (1992) who performed time to contact judgment tests of objects travelling in virtual 3-D space. The superior timing response in head-on approach was explained by the fact that the local tau indicating the rate of symmetrical optical expansion is perceived most accurately in a head-on approach. There were perceptual biases according to the approaching direction. Whereas a head-on approach showed an under-estimation of time-to-contact, motion in oblique and transverse planes caused an over-estimation of time-to-contact judgment. On the other hand, Coker (2005) showed no differences in coincidence timing judgment regardless of whether the stimuli approached the performer or moved away from the performer.

Interestingly, Isaacs (1990) employed two target displays so that a performer had to estimate the timing at the intersection of not one, but two converging objects (e.g., spatial and temporal anticipation of the arrival of a slower moving target with the control of a faster moving target with a faster moving target). This task was used to simulate anticipatory timing behavior in American football, where the quarterback must not only anticipate his own response time, but must also anticipate the movement time of the receiver and the thrown ball's flight time so that both receiver and ball arrive at the designated location at precisely the same time. Angle of

approach was manipulated. Whereas earlier research reported that as angle of approach increases there is a corresponding increase in timing error, this study showed greater coincidence timing error (i.e., AE and VE) only when the two objects moved at 180 ° with respect to the participants. Unlike previous studies suggesting the performer's inability to view both moving stimuli simultaneously as the reason for timing difficulty, Isaacs (1990) argued that the difficulty in perceiving the proportional distance along the runway to which the target stimulus is approaching might be the reason. Consistent with this explanation, participants formed a response strategy (e.g., proportional distance strategy) and then utilized knowledge of results after they internalized the speed of the target and the stimulus under their control and the relationship between the two. Therefore, the situation when the teammate is running directly toward the thrower would be the most difficult to time coincidently when the interception location needs is specified.

On the other hand, studies of interception of moving targets have concentrated on how people adjust movement kinematics according to the variations in spatial (Brouwer, Smeets, & Brenner, 2005) and temporal (Dubrowski, Lam, & Carnahan, 2000; Port, Lee, Dassonville, & Georgopoulos, 1997) information from the moving target. Two different types of interceptive action were employed according to whether the coincidence anticipation of a moving object is attained with the hands directly or with a projected object indirectly. The major independent variables that have been manipulated include target speed (Tresilian & Lonergan, 2002), size of the effector (i.e., bat) (Tresilian & Plooy, 2006), and speed and size of the moving target (Tresilian & Houseman, 2005).

Target velocity is a main variable influencing the perception and action process in interception tasks. Similar to coincidence timing tasks, Fleury et al. (1998) found that absolute

25

spatial error was greater in a slow target condition and there was a temporal bias toward early aiming with slow targets and the late aiming with fast targets. There was a strong association between target speed and movement time. Movement initiation time (Port et al., 1997) and duration of interception responses tend to become shorter with faster target speeds (Tresilian & Houseman, 2005; Tresilian & Lonergan, 2002; Tresilian & Plooy, 2006; van Donkelaar, Lee, & Gellman, 1992). However, shorter movement time do not appear to be associated with spatial accuracy requirements (e.g., target size), but with temporal accuracy demands (Tresilian, Plooy, & Carroll, 2004). The formation of an appropriate response is influenced by the predictability of target velocity information (e.g., random versus predictable order of target speed presentation). When target velocity information was predictable, shorter time intervals between target motion detection and the response was observed (van Donkelaar et al., 1992). In addition, the optical variable tau, which varies with target speed, was not the required variable to control the interceptive grasping movement. The fine tuning of hand aperture scaling was possible without perceiving the change of ball's rate of expansion (Savelsbergh et al., 1991).

How changes in target velocity characteristics (e.g., changes in velocity profile) influence the interception movement kinematics has also been studied. Dubrowski and colleagues (2000) manipulated the time that the target arrives at its peak velocity. The assumption was that the kinematics of the interception movement will vary as a function of target velocity if participants are able to use information about the changing velocity of the target's trajectory. Significant target velocity effects on movement initiation time were found, indicating the existence of on-line processing of visual information. From the movement initiation data, it was also suggested that the information about the target motion characteristics was achieved in the early phase of the target's trajectory.

Whether acceleration or deceleration information of the target is used to control the interceptive movement was examined both for both manual and indirect interception tasks (Benguigui, Ripoll, & Broderick, 2003; Port et al., 1997). In a manual interception task, Port et al. (1997) found that the time required for the stimulus to travel a threshold distance was the determinant of response initiation, so that the people relied more on velocity of the target, rather than acceleration information. Similar findings were observed in an indirect interception task. Benguigui et al. (2003) had participants roll a tennis ball to intercept a moving stimulus anywhere within an interception zone with a horizontal extension of the forearm. Nine accelerations were used and temporal error as well as time to movement initiation, ball release, and ball contact was measured. Statistical analysis of constant timing error showed a main effect of acceleration, indicated by an overestimation for the decelerating trajectories and underestimation for the accelerating trajectories. Analysis of the movement data indicated that there were no specific adjustments of the movement with respect to the value of the first order of time to contact information (i.e., time to contact at the movement initiation) and that the movement is produced at a constant time. So, in indirect interception tasks, the detection of velocity modulation is not directly based on acceleration information but rather based on a perception of the differences between velocities at distinct instants. The estimation of time intervals of the visuomotor delay, the movement time, and the time to the ball's trajectory is incorporated into the time instant to initiate the movement and no further adjustment was observed during the propulsion period.

Overall, the results were consistent with previous findings in that the visual system does not seem to sense acceleration information directly even if it is possible to discriminate through successive comparisons of the stimulus's velocity (Werkhoven, Snippe, & Toet, 1992). The

detection of acceleration does not guarantee a minimization of errors in action. However, for the successful performance in football passing or trap shooting where the receiver or clay pigeon's velocity are not constant during the course, the players might have to consider these variations 'by learning some method of aiming and acting', rather by psychophysical detection mechanisms.

Besides the influence of temporal variations of the moving target on interceptive action, Brouwer et al. (2005) investigated the effects of changes in the target's spatial dimensions as well as speeds on movement time. Four different targets moved from left to right at two different speeds. The correlation between movement time and hitting precision in the horizontal and vertical direction as well as the movement variability was obtained. Variations in the target's width influenced both spatial and temporal accuracy, whereas the height variation only affected spatial accuracy. As movement time increased, timing variability also increased, but spatial variability decreased. It was stated that only the target speed and size information was used to optimize intercepting strategy.

Response Factors in Interceptive Actions

Characteristics of the motor response in coincidence anticipation influence performance. In throwing Fleury and Bard (1985) found that the prediction of an environmental event (i.e., external anticipation) leads to improve performance in comparison to the anticipation of the performer's own movement (i.e., internal anticipation). However, movement time and movement velocity can independently influence timing accuracy. It has been demonstrated that decreases in timing error were associated with decreases in movement time or increases in movement velocity (Newell, Carlton, Carlton, & Halbert, 1980; Newell, Hoshizaki, Carlton, & Halbert, 1979). These finding suggest that response factors such as movement velocity and movement amplitude are

28

important factor in coincidence anticipation performance (Magill, 1998).

It was proposed that the balance between perceptual and motor contributions to coincidence timing performance vary as a function of practical task conditions. For example, whether the movement is controlled by open-loop or closed-loop control depends on the type of movement, the time available, and the amount of practice. Williams (2000) examined the effect of movement extent on coincidence timing in a soccer kicking task. Absolute timing error was greater when the kicking action required two or more steps in comparison to a single step. It was also reported that participants concentrated more on modulating the speed and force of the striking action of the kick to reduce timing error rather than focusing on the spatial target.

As a further modification of response factors in coincidence timing, the type of movement has been examined with a focus on the size and complexity of the movement (e.g., key press with a finger or arm movement, whole-body movement such as kicking or throwing). When the type of movement includes larger movements (i.e., striking or throwing), greater timing error and greater variability have been found in comparison to those of simple movement responses (e.g., button press) (Fleury & Bard, 1985; Peters, 1997; Williams & Jasiewicz, 2001; Williams, Jasiewicz, & Simmons, 2001). The rationale for the differences in variability was that internal anticipation of the larger movements would require more sensorimotor integration so that it may be difficult to achieve coincidence timing with a moving object.

Differences in the nature of the responses were suggested as a reason for the contradictory results such as Shea et al. (1981) which showed no effects of target speed on spatial and temporal accuracy. Tasks used in previous studies required mainly a button-press or release or a single-joint response which could be more sensitive to target speed than a complex multi-joint task. Large biases or constant errors due to late responding at the fastest speeds

29

contributed to the timing error increases when the task was a simple button-press (e.g., Coker, 2006; Park, 2003; Peters, 1997). This relationship between target speed and temporal bias, however, is quite inconsistent with those studies showing larger AE and VE in larger movement conditions (i.e., striking or throwing vs. button press) where greater sensorimotor integration is assumed to be required so that accurate coincidence timing is harder to achieve. In addition, with regard to the temporal bias, another possibility was that the participants might have adopted a spatial landmark to control their response, because in the case of the complex task the generation of movement based on a spatial reference stabilizes the response. That is, the more uncertainty, the less visual guidance.

Perception-Action Coupling in Timing Tasks

It is known that the variability of response timing errors in coincidence anticipation tasks is five or six times greater than that observed in interceptive action tasks performed under the same stimulus conditions (Bootsma, 1989; McLeod, McGlaughlin, & Nimmo-Smith, 1985; Tresilian, 1994b). Two possible reasons for these differences were suggested by Tresilian (1995). First, coincidence anticipation timings are less well practiced than are interceptive actions and response variability decreases with practice. Second, in coincidence anticipation tasks the available feedback is not as specific as that available for interceptive actions, so that there may be differences in the extent to which temporal precision is refined. For example, a coincidence anticipation task, where only a part of the trajectory of the object is permitted to be seen (i.e., motion prediction paradigm), leads participants to rely on the perceptual anticipation process, as compared to an interceptive action task where the participants are able to see the object through the whole trajectory so that the receptor anticipation process is emphasized. These differences may result in actors using different control mechanisms in different conditions (Williams et al.,

30

1999).

It is also important to note that coincidence anticipation and interceptive action tasks differ in the degree of de-coupling between information and movement. Coker (2006) argues that this results in differences in sensorimotor demands. The degradation of the performance (e.g., accuracy and variability) as information-movement becomes de-coupled (Bootsma, 1989) supports the ecology of information as "'specificational' in regulating behavior under the natural task constraints of interceptive actions" (Davids, Button, Araujo, Renshaw, & Hristovski, 2006, p. 80).

Because representativeness is defined as the generalization of task constraints in specific research settings to performance constraints outside the experiment, it seems reasonable that maintaining key sources of perceptual information and action together would be a principle for designing representative tasks to study interceptive actions (Davids et al., 2006). Therefore, when the movement-dependent use of perceptual information is possible, the performer would develop a stronger coupling of movement to relevant sources of perceptual information.

One criticism of coincidence anticipation research is that computer simulated target presentations, which have been widely used, may de-emphasize certain sources of information available in real life circumstance. A two-dimensional display of target information inhibits the performer from using depth information or binocular invariants (Wann, 1996) and its quality is quite impoverished compared to those in natural settings.

Control of the Point of Interception

Unlike coincidence anticipation tasks, where the point of interception is predefined and no direct synchronization between the target and effector in space is required, in interception tasks it is possible to make a functional distinction between timing (when) and positioning

(where) (Tresilian, 1999). How to achieve the positional information, which tells one where to do something, is an important part of interception performance. Research on perceiving and acting has manipulated interception location either directly or indirectly.

In aiming tasks, visually specifying either target or non-target information influences outcome accuracy. Davis (1984) found that precise visual information about the center of the target is important in controlling the accuracy of throwing. When precise target center information was unavailable radial error increased. The presence of non-target landmarks influences movement planning and outcomes (Obhi & Goodale, 2005). It was found that the presence of non-target landmarks was effective only when the movement was executed to a remembered target, but not in real-time pointing movements. Although accuracy (e.g., absolute error) was improved in both delayed and immediate actions when non-target landmarks were presented together with the target, movement precision (e.g., variable error) was enhanced only in delayed pointing. Because the landmarks were never presented during the execution of the movement, the effect of landmarks was associated with the initial encoding of target position.

Eye movement control strategy can switch from foveating the interception location to tracking the moving target with small changes in task constraints. Brenner and Smeets (2011) had participants intercept a moving target moving either behind or in front of a transparent barrier. An opening in the barrier marked the interception location. When the moving object moved behind the barrier a hand-help stylus had to be moved through the opening to contact the target. When the moving target moved in front of the barrier the stylus was used to hit the target through the opening in the barrier. When the target moved behind the barrier performers tended to fixate on the interception point. In contrast, when the target moved in front of the barrier performers tended to track the moving target. Greater interception accuracy was found when

performers fixated on the interception point.

On the other hand, constraints imposed directly on movement production influenced spatial variability of interception location and therefore interception accuracy (Tresilian, Plooy, & Marinovic, 2009). Allowing the moving object to be intercepted at any space and time along the target motion increases aiming variability with respect to the environment or "laboratory space". Tresiliam et al. (2009) showed changes in variability by either loosely or tightly constraining the movement path and thus the available interception area. The reduction of spatial variability in laboratory space associated with the constrained movement path resulted in increased temporal variability in hitting the moving target. Overall, constraining interception location may play a beneficial role in producing a quick, pre-planned movement. But, movement path constraints led the performers to interdependently compensate the spatial and temporal accuracy.

<u>Gaze Control and Information Processing</u>

Characteristics of Eye Movements

Information obtained from the human visual system plays an important role in controlling movements. The term "visuomotor control" is defined as the process whereby visual information is used to direct and control movements (Vickers, 2007). Because the eye is the only system which receives visual information, the range and amount of available visual information is determined by attentive control as well as the physical limitations of the eye. Generally, the visual field, which is defined as the total amount of light that stimulates the eyes at any moment in time (Vickers, 2007), is divided into three regions: foveal, parafoveal, and peripheral (Rayner, 1998). It is generally accepted that the visual angle of foveal vision is limited to about 2 to 3 degrees and the parafovea extends out to 5 degree on either side of the fixation point. As the

33

visual field becomes wider, acuity gets poorer. Thus, the acquisition of visual information is constrained by the control of gaze which is represented by the process of directing the gaze to objects or events within a scene in real time.

Basically, four types of eye movements are considered in studies of visuomotor behavior: saccade, fixation, pursuit, and vestibular eye movements. Saccades are ballistic eye movements whose function is to bring a new object of interest to the fovea. A single saccade takes only about 150-200 ms to be planned and executed and reaches speeds of up to 900 °/sec (Palmer, 1999). Because the eyes move so quickly across the visual stimuli, only a blur would be perceived during the saccadic eye movements and none of visual information is processed during this span. This phenomenon is called saccadic suppression (Matin, 1974). On the other hand, the eyes are never perfectly still because there are small but continuous movements of the eyes (e.g., nystagmus, drifts, and microsaccades). However, the eyes are considered fixated and thus information processing is permitted if the gaze is held on an object or location within 3 degrees of visual angle for 100 ms or longer (Carl & Gellman, 1987). The location of a point of gaze (POG) is typically assumed to index the focus of attention (Duchowski, 2007), when a visual fixation occurs. So, the POG is often assumed to include the most important task relevant information. Pursuit eye movements occur when the eyes follow a slow-moving object, so that a stable retinal image is maintained. The ability of the visual system to track an object depends on its speed. If the speed exceeds the maximum velocity of pursuit movement (i.e., about 30 °/sec) saccades to catch-up to the moving object are generated (Palmer, 1999). So, when tracking a moving target is required, a catch-up saccade brings the target on the fovea and then smooth pursuit movements maintain the stimulus on the fovea. Finally, if smooth pursuit does not match the target velocity precisely enough, corrective saccades are generated to reduce the accumulated

position error (Klam, Petit, Grantyn, & Berthoz, 2001). A fourth type of eye movement, vestibular eye movements, keep the eyes fixated on a particular location when the head or body is being rotated. Because this movement is reflexive via information coming from the vestibular system in the inner ear, the head, body and oculomotor system can be coupled together with a lag of approximately 16 ms (Palmer, 1999).

Measuring Eye Movements and Criticism

Because eye movements can be controlled volitionally and tracked by modern technology with speed and precision, the information achieved from POG has been considered as meaningful in that it represents the human perception-action interactions with the environment. Eye movements have been monitored in many different ways. Four different methodologies have been developed: electro-ocuolography (EOG); sclera contact lens/search coil; photo-oculography (POG) or video-oculography (VOG); and video-based combined pupil and corneal reflection (Duchowski, 2007). Because there are still many advantages and disadvantages among these methodologies, no measurement standards have been adopted. The most popular technique in motor behavior has been the use of the head-mounted corneal-reflection method. As the position of the corneal reflection in relation to the center of the pupil remains constant during head translation, but moves with eye rotation, point of regard can be extrapolated. Also, an additional "scene camera" points at the subject's field of view from the subject's perspective, thus allows point of fixation to be superimposed on the scene camera's image regardless of where or how the subject moves (Richardson & Spivey, 2004). Then, eye displacement data represented as a moving cross-hair or cursor are combined with head position and orientation to produce data on fixation location, duration, and order.

Even though the video based system combines information regarding eye fixations, head

35

position and key locations in the image being viewed by the subject, there have been issues regarding the range and accuracy of the measurement, and especially the interpretation of eye movement data. The primary limitation of eye movement recording techniques is the extent to which the differences in fixation characteristics implicate differences in information extraction. The assumption that the point of fixation indicates the information to be extracted ignores the importance of peripheral information. Seeing that observers might be able to shift attention to different sources in the environment without moving their eyes, the differences in "looking" and "seeing" must be considered when the eye fixation information is interpreted. There are also questions about whether information in the parafoveal region is actually being picked up and utilized (Abernethy, 1988). Given these limitations, the combined use of eye movement recording with other measures of information extraction such as film occlusion and verbal reports was suggested (Abernethy & Russell, 1987; Williams, Davids, Burwitz, & Williams, 1993).

Additional issues in visual search studies include ecological validity, instruction delivered to the subjects, and small sample size, which result in difficulty in making inferences from the eye movement data. For instance, the use of a video display in studying anticipation generated a fundamental issue with regard to ecological validity. Many studies presented a static slide or dynamic films. The absence of temporal, directional and sequential movement information as well as the use of impoverished displays were criticized in that they result in unrealistic visual search strategy (e.g., fixation frequency and search rate) (Williams et al., 1999).

Gaze Control and Interceptive Timing

Visual sensitivity in humans declines, in general, with retinal eccentricity. Foveal and parafoveal visual fields have a higher threshold for spatial determinants such as discriminating

contrast, binocular disparity, and spatial resolution. In terms of temporal aspects of control, peripheral vision reaction time was found to be longer compared to central visual reaction time (Ando, Kida, & Oda, 2001). Use of visual information from the central visual field was more effective to correct errors online in tasks that require the control of movement amplitude (Lawrence, Khan, Buckolz, & Oldham, 2006). Also, while time to contact, rate of expansion, and size can be processed simultaneously or independently in foveal vision, this independence decreased as eccentricity increased (Regan & Vincent, 1995). Results from previous studies, in general, support the superiority in visual information processing through foveal vision.

There have been somewhat inconsistent results in coincidence timing judgment when the use of specific visual tracking instruction was considered. Matsumiya and Kaneko (2008) demonstrated that when people judge TTC of an approaching object pursuit eye movements improved TTC judgments in comparison to a fixed eye position. It has been argued that extra-retinal information from the pursuit eye movements provides rate of change information regarding visual direction of the object. In addition, Park (2005) used three different instructions for gaze control: natural (no-instruction), catch-up (e.g., tracking), and predictive (e.g., fixation). In natural and catch-up conditions errors became larger as stimuli speed increased. Errors decreased as stimuli speed become faster for the predictive strategy. Therefore, the effect of stimuli speeds on timing accuracy might change according to the eye movement patterns and the optimal gaze control strategy varies depend on the stimuli speed. The importance of visual information in coincidence timing judgment is not limited to the moving stimuli itself, but incorporates the information coming from the peripheral area of the fixed environment (Tresilian, 1994b).

On the other hand, Peterken et al. (1991) using two different instructions for gaze

control (i.e., track and not to track the target) did not produce any significant differences in timing accuracy. Long and Vogel (1998) also reported equivalent results in two test conditions, one where tracking of moving stimulus was required and a second condition where tracking strategy was not specified. The consensus of these two studies is that eye-movement tracking may not be a crucial component on anticipation timing. Although following the target with the eyes may be preferred and an effective way of estimating coincidence timing, beyond a certain degree of target speed, alternative strategies (e.g., predictive 'jump' to the final destination) may be preferred. Other factors such as knowing the expected target velocity before the trial also enables the task to be accomplished. It would be less likely to continuously track the target if the task condition becomes more predictable. However, the Peterken et al. study was limited in that they used a small computer screen with very low-velocity targets.

Gaze control is influenced by the direction of target motion. The retinal motion involved in tracking an oncoming target is different from tracking a horizontally or vertically transposed target (Bennett, Baures, Hecht, & Benguigui, 2010; Long & Vogel, 1998). The properties of eye pursuit in the horizontal direction are quite different from those in the vertical direction. Greater pursuit gain in the horizontal direction and larger eye accelerations for pursuit initiation in the vertical direction have been shown (Rottach et al., 1996). Additional studies support the notion that horizontal tracking is superior to vertical tracking (Collewijn & Tamminga, 1984; Gronqvist, Gredeback, & von Hofsten, 2006; Soechting & Flanders, 2008). In sports situations such as ice-hockey goaltenders (Salmela & Fiorito, 1979) and soccer goaltenders (McMorris, Copeman, Corcoran, Saunders, & Potter, 1993; Williams & Burwitz, 1993) better prediction of the horizontal direction of the shot, as opposed to the height of the puck (or soccer ball) was also reported.

Visual search strategy refers to the way in which the eyes are used to search the display or scene for relevant information to guide action (Henderson, 2003). This process is conducted by moving the eyes about the visual environment (i.e., through saccades and smooth-pursuit) in an effort to locate and attend (i.e., fixation) to the most information rich areas. To ensure efficient tracking of a moving object, however, movement programming must include elements of prediction due to the intrinsic sensorimotor delays. The time delays, such as latency for the initiation of smooth pursuit eye movements and saccadic initiation, are due to response latencies to motion signals in visual cortical areas (Maunsell & van Essen, 1983; Newsome, Wurtz, Dursteler, & Mikami, 1985). In addition, time delays also arise from the time to estimate the key parameters such as speed and direction of a visual motion signal (Mrotek et al., 2004). Therefore, the neural process should include an extrapolation of future action from the present and/or past information.

Anticipatory Saccades

Eye movements may reveal some motor correlates of the intrinsic prediction process (Klam et al., 2001). Because information can be obtained only during the time span when the eyes are fixated, the perceptual process in tracking may be indicated by the performer's eye movement characteristics. Park (2003) argued that systemic changes of average velocity of saccades and of the frequency of saccades implicate the strategic movements of the eye, so that it may demonstrate adaptive control mechanisms. The saccadic system does not operate autonomously, but reflects internal processes. The activation pattern of the lateral intraparietal area of the brain, which functions in the planning and deciding of certain movement types (e.g., saccades, reach or grasp) before movement is generated (Shadlen & Newsome, 1996), indicate

that targets for saccades are selected ahead of movement generation which reflects purposeful gaze control in the sensorimotor transformation process. When a series of movements are required, the eyes tend to reach the next object in the series before the preceding movement ends, so that eye movements interact with motor sequences and thus lead the action.

As the environment becomes dynamic, that is, the object, the performer, or both move in the environment, sophisticated eye movement control is required to meet the spatial and temporal requirements. Looking at the right space at the right time with anticipation would be essential for the error-free performance. Ball sports provide examples in which the task is to intercept a moving ball and hit it with a controlled movement. For example, in cricket (Land & McLeod, 2000), the expert batsman track the initial portion of the ball flight with smooth-pursuit eye movements and then produce an anticipatory saccade to the predicted bounce point. After that, the final portion of the ball flight information (e.g., for a period up to about 200 ms after the bounce) was obtained by a combination of eye and head movements. Because the main differences in oculomotor behavior in expert and amateur batman were the speed and variability of the initial saccade, the superiority in producing pursuit tracking and saccades to the expected bounding point, rather than tracking ability after the bounce, was proposed as a determinant of performance level. Similar gaze behavior was observed in many other sports situations where a common sequence of detection, pursuit tracking, and an aiming phase exist such as hitting a baseball (Bahill & LaRitz, 1984; Shank & Haywood, 1987), receiving a volleyball serve (Vickers & Adolphe, 1997), and ice-hockey goaltending (Panchuk & Vickers, 2006). These studies argue that detailed information from the approaching ball, such as the ball's position and velocity, can be achieved by foveal vision, even with a single fixation, and suggest what part of the ball flight is important to the performer.

Fixations are frequently directed to places where there is no target object. Anticipatory saccades produced by squash players (McKinney et al., 2008) were directed to the front wall and then moved to the side or back. These saccades were made to a point in space where the ball would soon pass (e.g., 220 ms later). McKinney et al. stated that predicted eye movements are based on a sophisticated and flexible model internalized through practice, thus the experience with the ball's dynamic properties as well as the ability to rapidly update this model when errors occur are essential for successful performance.

Predictive saccades play an influential role in determining directional accuracy in interceptive pointing. Mrotek et al. (2004) revealed that predictive aiming of the direction of moving stimuli was highly correlated with the location of gaze. When participants were asked to point the final direction of a moving stimulus, small but systemic errors which overestimate the target's change in direction were found. Because the target was occluded after it changed direction (50 to 400 ms later), participants had to rely on saccades, one large saccade close to the designated target area (e.g., perimeter of the circle) followed by a small second saccade directing gaze to the target, in order to produce a correct finger pointing on the screen. In line with this notion, the results showed a correspondence between the location of gaze and the location where the finger contacted. Gaze control where the moving stimulus followed a circular path and participants were required to point at the target with the finger, indicates that the target motion signal extracted at the moment of hand movement initiation was used to predict the circular path of the moving target (Soechting & Flanders, 2008).

The stabilization of anticipatory saccades at the time of movement initiation has been shown as an essential factor for the accurate performance. Rodrigues et al. (2002) found that the eye and head are stabilized as the arm moved to stroke a table-tennis ball and the stabilization

lasted for about 100 ms, up until a point 30 ms before ball-bat contact. It was suggested that because the ball moves across the retina when the head and eyes are fixated, increased sensitivity to ball motion through peripheral vision enhances the process of obtaining information from the ball's final trajectory. Furthermore, Lafont (2008) studying the tennis forehand found that maintaining fixation on the contact zone and stabilizing the head and eye until the completion of the hitting action were associated with the level of skill expertise.

Fixation Strategy in Aiming

The coordinated fixation sequence of gaze control to particular task-relevant points allows time for the brain to assess the geometric relationships between the external environment and the internal representation of it (Johansson, Westling, Backstrom, & Flanagan, 2001). The relationship between visual search strategy efficiency and expertise presents a dilemma, 'which is attained first?'. Research consistently shows that skilled performers exhibit fewer fixations of longer duration (Mann, Williams, Ward, & Janelle, 2007). Non-experts generate more fixations of shorter duration and are considered less efficient. Producing more fixations and thus more saccades results in the non-expert extracting less information as compared to the expert. For example, skilled performers in pistol shooting and golf putting fixated their gaze on the target or the ball. Unskilled performers tend to gaze at the gun or the golf club, which is in motion (Ripoll, Papin, Guezennec, Verdy, & Philip, 1985; Vickers, 1992).

While traditional eye-tracking studies have concentrated on measuring the number, duration, and frequency of visual fixations, the location of fixations, and saccades, one stream of recent research has focused on a measure of the last fixation before the movement is initiated. The last fixation was considered as the period where associations between visual attention and information processing occur. Vickers (1996), in a pioneering study constructing associations

between gaze behavior and performance, examined the relationship between control of gaze fixation and skill level by examining the time of final fixations in basketball free throw shooting. Gaze behaviors of elite basketball athletes were recorded during the completion of 10 successful and 10 unsuccessful free throws. She found that the differences in duration of the final fixation before movement initiation significantly influenced performance accuracy. Because better performers showed a tendency gaze on the target early in their search patterns and then fixate on the target until movement initiation, it was argued that fixations that are relatively longer during the preparatory phases of the task are highly correlated with increased accuracy. It was suggested that these fixations provide the chance to process task-relevant cues more precisely. Thus, differences in skill level did not originate from overall surface features of the free throw (e.g., skill or accuracy) but in the control of final gaze fixation. In addition, the control features of last fixation were associated with the intra-trial variability (e.g., accuracy). That is, earlier onsets and longer durations of final fixations were highly correlated with accuracy. It was postulated that the final fixation duration (termed quiet eye) is the time period for programming movement parameters as well as location, duration, and temporal control with respect to the movement phases (Panchuk & Vickers, 2006; Vickers et al., 2000).

According to Vickers (1996), in order not to be distracted from the task irrelevant cues, the performer suppressed vision after the movement is initiated. The location-suppression hypothesis was proposed based on the notion of Schmidt (1988) that while the motor program was organized and implemented in the movement execution phase, "sensory information can modify the central command structure as the movement is unfolding" (p. 22). Therefore, in aiming tasks such as the basketball free-throw, which has relatively long movement time, the probability of being distracted from task irrelevant cues becomes higher. Filtering out the new

visual information in the execution phase ensures a high level of accuracy. According to the location suppression hypothesis, long durations of final fixation during the preparatory phase must be made to specific target locations and then maintain this fixation with slow movements in the impulse phase. Further studies in basketball, pistol shooting, and golf putting supported this hypothesis (Ripoll, Bard, & Paillard, 1986; Ripoll et al., 1985; Vickers, 1992). No evidence for Vickers's suppression hypothesis was obtained, however, when the task employed did not include any body parts or a piece of equipment that interferes with the performer's view of the target such as billiards (Williams et al., 2002). Thus, it was suggested that the suppression hypothesis may be specific to a certain type of task.

On the other hand, Oudejans, Langenberg, and Hutter (2002) examined whether the target can be seen until the last moment of ball release in basketball jump shooting by manipulating viewing time. It was found that vision only during the last 350 ms before ball release resulted in accuracy comparable with full vision. Occluding vision of the final 350 ms before shot release impaired the performance severely. Based on this finding, the authors stated that the vision of far target aiming in the basketball jump shot is controlled in a closed-loop fashion (i.e., online processing of visual information) which is in contrast with Vickers (1992; 1996). These findings were replicated by Oliveira, Oudejans, and Beek (2008). So, depending upon the nature of the task, different mechanisms of visual information control in far target aiming were suggested.

Since Vickers (1996) established the theoretical foundations for gaze fixations and motor performance, a large number of studies were conducted to reveal the exact nature of final fixation duration for different classes of movements and tasks. For aiming types of tasks, besides the basketball free-throw (Vickers, 1996), further studies reinforced the notion that longer

44

fixation times right before movement initiation are a critical factor determining accuracy (Behan & Wilson, 2008; Janelle et al., 2000; Vickers, 1992; Vickers et al., 2000; Williams et al., 2002). For instance, Williams et al. (2002) examined the importance of long final fixation durations in time-constrained aiming situations. Final fixation duration decreased with time pressure. Final fixation durations were related directly to the outcome of the performance. That is, time pressure resulted in shorter final fixation durations and poorer performance regardless of the performers' skill level.

Furthermore, the temporal control of final fixation duration with regards to the phases of movement execution was proposed as a critical parameter to achieve accuracy in far target aiming. Vickers et al. (2000) measured final fixation duration in dart throwing. It was hypothesized that if dart throwing is controlled using closed-loop control mechanism, the final fixation should remain on the target throughout each of throwing phases. Otherwise, the movement would be controlled open-loop, and if so, the final fixation should occur only in the early phase of the throwing movement (i.e., alignment and flexion phase of the arm), not during the movement execution phase. Optimal onset, offset and duration of the final fixation before the extension phase of movement turned out as a critical factor determining the performance outcome. Because the final fixations occurred well before the final extension phase of the movement, open-loop control was supported.

In summary, although diverse aiming skills have been tested (e.g., archery, basketball free throw, billiards, dart, golf putting, and rifle-shooting), in those studies the targets to be aimed were all stationary. In addition, various mediating variables which require the control of gaze fixation to be adapted to the spatial and temporal characteristics of the tasks, question how robust the associations of the gaze fixation with aiming performance are. Therefore, it seems

45

realistic that the process of extracting the task relevant visual information would differ for moving targets. The optimal fixation strategy may differ for fixed and moving targets.

Fixation Strategy in Interception

The gaze fixation strategy in interceptive action has been investigated mostly under conditions where the target is on a head-on approach to the performer such as serve-receiving, hitting, and goaltending. In the forehand serve return task of table tennis, Rodrigues and colleagues (2002) found that the final fixation strategy was disrupted by the presentation of a cue light. Eye fixation patterns (e.g., location and duration) were altered according to when the cue was given to the performer (e.g., pre, early, and late cue). Plots of gaze relative to the ball showed that in the pre-cue condition (cue light before the serve) the ball was tracked and then gaze was moved to the correct side to receive the ball, in the early-cue condition (cue light during the initial portion of ball flight) gaze shifted quickly to the ball, and in the late-cue condition (cue light during the final part of ball flight) highly variable and smaller gaze movements were detected. The results indicate that the delayed information regarding the required movement direction was associated with reductions in performance accuracy mainly due to the reduced final fixation duration and a lack of eye-head stabilization with a late-cue.

The importance of fixation locations in interceptive tasks has also been addressed in ice-hockey goaltending (Panchuk & Vickers, 2006) and volleyball serve receiving (Vickers & Adolphe, 1997). Panchuk and Vickers (2006) measured the gaze behavior of ice-hockey goaltenders in performing "saves" against wrist shots from 5 and 10 m. Because the shot reached the net within 150 ms or 200 ms depend on the distance, the flight duration of the puck was close to the threshold of the visual reaction time. The relationship between saves and the shooter's movement duration, shooting distance, and the ability to tracking the puck in flight were weak.

Instead, the ability to maintain a longer fixation on the puck or stick before initiating the saving action was the main factor explaining the ability to stop the puck. Thus, the findings indicated that the earlier onset and the longer duration of the final fixation at the critical spatial location were important in tracking the puck in flight.

The results from interception tasks where the target moves towards the player shows that maintaining point of gaze at a specific spatial location provides a direct relationship with performance (e.g., ball or puck). However, analysis of the results has been dedicated to reveal skill-based differences. The superiority of experts in fast ball sports has been shown in using pre-ball flight information, specifically, kinematic information present in an opponent's movements prior to the availability of any ball-flight information (Abernethy, Gill, Parks, & Packer, 2001; Shim, Carlton, Chow, & Chae, 2005). How the visual gaze system extracts motion information throughout the ball flight needs to be examined further in conditions with different constraints. Thus, it seems premature to confirm the excellence of the quiet eye strategy as a general gaze control strategy in interception and targeting tasks.

<u>Constraints on Movement Organization</u>

One of the basic assumptions in discussing human movement is that human movement is viewed within the context of a self-regulating system. That is, "movements are the behavioral outcomes of a complex process having to account for the imposition of environmental constraints, biomechanical constraints, and morphologic constraints for each individual performer and each performance trial and task" (Higgins, 1977, p. 7). Therefore, regardless of the levels of analysis (i.e., behavioral, movement, muscular, or motor level), the behavior will be meaningful when the selection of adequate movement class is deemed in conjunction with the constraints imposed upon the movement.

Constraints on Action

The role of constraints on motor behavior comes from the question of how coordination emerges within and between the many different subsystems of the human motor system (Williams et al., 1999). As coordination is defined as 'the process of mastering redundant degrees of freedom of the moving organ' (Bernstein, 1967, p. 127), the extent to which the movement is coordinated with the task is dependent upon the ability to deal with imposed constraints at a given situation. Three categories of constraints interact together to determine the optimal pattern of coordination and control for a given activity (Newell, 1986): organismic, task-related, and environmental constraints.

Organismic constraints indicate the individual's characteristics including physical, cognitive, and emotional aspects. So the perceptual processes and decision-making as well as anatomic considerations belong to the scope of organismic constraints. On the other hand, environmental constraints are considered those that are external to the organism. Although they are not mutually exclusive, environmental constraints can be distinguished from task constraints in that the former is not manipulated by the experimenter in general and is relatively time independent. Environmental constraints incorporate gravity, natural temperature, natural light, and other environmental features, whereas task constraints include a goal of the task, rules of sports, and implements or machines used for an activity. Certainly, the environmental constraints will produce the highest degree of variation in pattern of movement within performers (Gentile, Higgins, Miller, & Rosen, 1975), because the pattern of movement should be adapted to the uniqueness (e.g., predictability) and the spatial and temporal variation of the environment. An individual's movement patterns also need to be varied between performances because the achievement of the task goal is the most important. So, the performer needs to optimize

performance within the imposed task constraints. For example, the optimum angle for projecting an object into space is dependent upon the goal of the task and the physical characteristics of the object. In addition, achieving maximum distance is the main goal in the shot-put and javelin throw, whereas maximum speed and accuracy are required in baseball pitching and tennis serving. However, depending on the interpretation of the imposed constraints as well as individual differences in organismic constraints, different pattern of coordination and control might emerge even for the same set of environmental and task constraints.

Because organismic, environmental, and task constraints interact together, the optimal pattern of coordination and control as well as the relative impact of each constraint vary according to the specific situation. Therefore, the constraints-led perspective considers behavior as being an emergent phenomenon, rather than as the result of an a priori prescription of command or knowledge-based structure.

Constraints on Visual Search Strategy

Newell's (1986) model of constraints on motor behavior contributed as a framework for conceptualizing the influence of constraints on visual search behavior. Not unlike motor behavior, factors such as the nature of the task, the environment, and the distinctive feature of the individual all influence the visual search strategy of the performer. Because Newell's approach is mostly constructed by concepts from dynamical system theory, the constraints should generalize to the emergence of coordination in visual search behavior. Consequently, the visual search strategy should not be interpreted as a top-down process, but rather as a self-organized product shaped from the constraints acting on the performer (Williams et al., 2004).

Recent empirical works have shown how three classes of constraints assist or hinder visual search behavior in sports and daily life contexts. First, task constraints such as instruction

resulted in more attention allocated on task relevant items and a reduced number of fixations on irrelevant object (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003). In addition, Huys and Beek (2002) examined how the relationship between point-of-gaze and ball movement in three-ball juggling changes according to the skill level and required movement pattern and tempo. Line of gaze and ball movement data were analyzed in two groups of jugglers. Intermediate and expert jugglers performed a three-ball juggling task with two movement patterns (standard and reverse cascade) and three tempos (preferred, slow, and fast). Experts tracked a ball less frequently and the point of gaze and ball movements were locked with a 1:1 frequency in the horizontal direction and a 1:2 frequency in the vertical direction. The higher juggling frequency caused fewer intersections of the line of gaze with the ball, but more time was spent with 'eyes on the ball'.

Task constraints in self-paced tasks such as the shot in billiards, the free-throw shot in basketball, or putting a golf ball induced the performer to use a specific information-movement coupling strategy consistent with the quiet eye strategy. Use of the quiet eye in self-paced task can be interpreted as constraining a performer to pick up important 'information-specifying variables', and enhancing a functionally stable information-movement coupling (Williams et al., 2004).

In externally-paced tasks, players demonstrated different visual search behaviors under changing task constraints. For the dynamic interpersonal situation such as anticipation of an opponent's pass direction in soccer (Williams & Davids, 1998; Williams, Davids, Burwitz, & Williams, 1994), as interpersonal distance decreases (e.g., 1 vs. 1, 3 vs. 3, or 11 vs. 11), players tended to rely more on using peripheral vision to obtain the motion information of opponents. Flexible visual search patterns were also employed in spatially and temporally constrained ball

hitting. In the tennis serve return (Singer et al., 1998), the dominant use of either foveal vision or peripheral vision was decided by the ball trajectory and velocity. From the ball toss to the moment of racket-ball contact, mostly foveal vision was used to track the ball and motion. Thereafter, an anticipatory saccade was made to the predicted bounce area or to the anticipated ball-racket contact point. Similar flexible characteristics of search pattern were also observed in situations where organismic constraints (e.g., anxiety, fatigue, intention, and skill-level) and environmental constraints (e.g., condition of image display and nature of the experimental setting) were manipulated.

<p style="text-align:center">Projectile Aiming</p>

Research on projectile aiming has been conducted in mostly stationary situations such as projecting an object (e.g., dart or ball) to a vertically or horizontally oriented target. Kinematic analyses are typically conducted to measure the extent to which the limb or whole body coordination contributes to the projecting velocity, distance, or accuracy. Higgins and Spaeth (1972) measured the consistency of dart throwing movement in two different conditions, stationary target and moving target (three different speeds). Comparison of movement patterns at the head, shoulder, elbow, and wrist revealed that in open skills movement patterns were matched to environmental conditions and moved toward 'diversity'. With a stationary target movement patterns moved toward 'consistency'. Mueller and Loosch (1999) described how throwing accuracy is controlled in vertical target aiming (e.g., dart throwing). Although there are infinite number of speeds and angles of projection to achieve the goal, a certain combination of the spatial-temporal pattern of movement (i.e., angle-velocity combination) ensures the target is hit regardless of when the dart is released. This is possible because the variations in release angle are compensated by velocity changes. This notion was supported by Smeets, Frens, and Brenner

<p style="text-align:center">51</p>

(2002). Because the variation (SD) in the vertical position of the dart on the board was not different from the variability in the horizontal direction, release timing does not appear to be a critical factor determining throwing precision. Variations in movement speed and analysis of release are greater than the precision of regulating the outcome itself because each of parameters can influence each other.

Aiming at a moving target has had little attention even in the category of interceptive action. The movement in interceptive aiming (e.g., football passing) is quite different from the targeting task (e.g., stationary target) as well as the interception task such as hitting or catching. Unlike the stationary target aiming and the interception of an approaching target, interceptive far target aiming includes wide-ranging spatial configurations among the target, interception point, and effector. These variations require visual information pick-up in space and time. As the target is set in motion, the direction, speed, and trajectory of the moving target must be analyzed. In addition, with a relatively long flight time, anticipation must be used to determine how long the effector takes to get to the interception point. Therefore, the prediction of interception location should result from the combination of spatial and temporal extrapolation of the target motion and effector movement.

Eye movement studies have stressed the importance of gaze location to be placed onto the location where the performer aims at the initiation of the aiming movement such as in archery, billiards, basketball free-throw, dart-throwing, and biathlon (Behan & Wilson, 2008; Vickers, 1996; Vickers et al., 2000; Vickers & Williams; 2007; Williams et al., 2002). However, as additional constraints are imposed on the factors closely related to the nature of the task, the required search patterns (e.g., predictive saccades) are required to be fit to the imposed constraints. Even to the same constraints, for example, the search strategy needs to be conformed

depending on the characteristic of the effector. It was noted that "The barrel must always be aligned precisely where your eye is looking. …… His eye should be fully occupied with the bird …… So the shooting man must keep his eye on the bird and ignore his gun" (Churchill, 1927, p. 46-48). It seems clear that if this type of crossing shot is done by the hand, a bat, or by a projectile, one might have to look far ahead of the target at the beginning of the movement because of the significant differences in effector speeds.

A quarterback passing in American football is the most representative task in the class of interceptive projectile aiming. It requires particular types of visual abilities and search strategy for the accurate perception of motion information. Because one of the most difficult dynamic skills is tracking an object that is moving away from the athlete, optimized focusing and tracking capacities are essential to accurately judge and complete the long pass. Quarterbacks that continuously struggle with this pass could have a deficiency in this skill (McKinnon, 2007). Further, critical skills that the quarterbacks must be able to do accurately are to judge the distance and speed of the receiver and throw the ball to the correct point. Any short coming in this area will result in incomplete passes or interceptions.

<u>Statement of Purpose</u>

Interceptive projectile aiming to a moving target, such as passing in American football requires that two objects meet at the same place at precisely the right time. These tasks typically require a rapid aimed movement that needs to be precisely timed and is guided in a visually open-loop manner (Carlton, 1981; Schmidt, 1968). It is assumed that the movement is preprogrammed before its initiation and that visual information obtained up until the moment of movement execution plays a critical role in successful performance (Marinovic, Plooy, & Tresilian, 2008, 2009; Tresilian & Houseman, 2005). Spatial and temporal accuracy are

53

influenced by constraints imposed by the moving target (e.g., Fleury et al., 1998; Tresilian & Houseman, 2005), the interceptive action required (e.g., Dubrowski & Carnahan, 2001; Tresilian & Plooy, 2006), as well as gaze control related to the moving target (e.g., Rodrigues et al., 2002).

Projectile interception tasks require the pick-up of visual information about the moving target and vision is also used in the control of the action. Land and McLeod (2000) suggest that cricket batsmen acquire detailed information of an approaching ball through foveal vision and, therefore, eye fixation location or point of gaze (POG) indicates the parts of the flight that are visually important (see also Amazeen, Amazeen, Post, & Beek, 1999; Huys & Beek, 2002). The final fixation before movement initiation is thought to be particularly important because response programming may occur at this time (Bakker, Oudejans, Binsch, & van der Kamp, 2006; Panchuk & Vickers, 2006; Vickers, 1992, 1996; Vickers et al., 2000; Williams et al., 2002). In these studies, skilled versus unskilled performers as well as accurate versus inaccurate responses demonstrated significantly earlier and longer fixations just before movement initiation.

Although diverse aiming skills have been examined (e.g., archery, basketball free throws, billiards, darts, and golf putting), the targets to be aimed were all stationary. In contrast, studies of eye movement in interceptive action have focused on tasks where the target approaches the participants such as in cricket batting (Land & McLeod, 2000), ice-hockey goal tending (Panchuk & Vickers, 2006, 2009), the table tennis forehand stroke (Rodrigues et al., 2002), and volleyball serve receiving (Vickers & Adolphe, 1997). For tasks with a relatively long object flight time, such as cricket, performers show a tendency to fixate near the object projection point and then produce a second fixation later in the flight. In cricket the second fixation is near where the ball hits the ground.

While studies of aiming and interceptive action cited in the previous paragraph have

indicated an important role for eye movement control, studies that have manipulated eye movement directly in a coincident timing paradigm have shown mixed results. Long and Vogel (1998) and Peterken et al. (1991) did not find a significant role of eye movement. Whether or not the eye tracked the moving object was not a critical factor in performance accuracy. In contrast, Bennett et al. (2010) showed that tracking the moving object with the eyes could facilitate performance in comparison to fixating on the arrival location, but only under relatively long periods of moving object occlusion. When participants saw object motion up until 0.6 s of the arrival location, accuracy as measured by constant and variable error, was not influenced by eye motion. There have been fewer studies manipulating eye movement behavior in interception tasks. Using a catching task Dessing, Wijdenes, Peper, and Beek (2009) did not find that fixation direction influenced interception performance.

Eye movement behavior and interception accuracy are influenced by the constraints imposed by the moving target (e.g., Fleury et al., 1998; Tresilian & Houseman, 2005) and the interceptive action (Dubrowski & Carnahan, 2001; Fleury et al., 1998; Tresilian & Lonergan, 2002; Tresilian & Plooy, 2006). Because eye movements cannot track a moving object using pursuit eye movements for target speeds greater than 30 °/s, anticipation processes must be used to produce saccadic eye movements. Information such as advance temporal cues about the moving target (Tijtgat, Bennett, Savelsbergh, Clercq, & Lenoir, 2010), spatial cues about the environmental layout (Morice, Francois, Jacobs, & Montagne, 2010), and task history (de Lussanet, Smeets, & Brenner, 2001) can be used to predict target motion leading to increased interception accuracy. While a number of studies have shown that advance information results in altered movement kinematics and increased accuracy (de Lussanet et al., 2001; Morice et al., 2010; Tijtgat et al., 2010), few studies have examined whether visual search pattern is influenced

by the availability of advance information about target motion. Given that advanced knowledge of target motion allows performers to modify movement kinematics, the extension of the effect of advance information to eye movement kinematics seems necessary to assess the coherence between perception and action system.

Vickers (2007) presented a gaze control framework for interceptive timing and targeting tasks. Consistent with model predictions there is considerable evidence that more accurate performance is associated with longer final fixations when an object moves toward the performer or when the target is fixed in space. In this dissertation I sought to extend this research to the study of gaze behavior in far horizontally moving target interception. The purpose of the studies performed in this dissertation is to examine how temporal and target constraints influence eye movement behavior and movement accuracy. In a series of experiments target motion predictability was systematically varied. In Experiment 1, target speed was varied using a participant determined interception point or a fixed interception point. Target speed was blocked so that target motion was highly predictable. In Experiment 2, target motion predictability was varied by presenting target speeds in a blocked versus random order. Also, the target spatial path and speed was manipulated within trial. It was anticipated that increased timing constraints caused by faster target speeds would be associated with a greater tendency to look at the point of interception and less time following the moving target. Greater target motion predictability will increase this tendency. Increased target speed was expected to result in greater spatial error and lower timing error in hitting the moving target. As target motion predictability increases spatial and temporal error will decrease.

EXPERIMENT 1. INFLUENCE OF SPATIAL AND TEMPORAL CONSTRAINTS ON VISUAL SEARCH STRATEGY

Introduction

Accurate perception of motion characteristics of the moving target is clearly the most important factor determining the quality of the interception performance. A primary variable influencing interception accuracy is the speed of the moving target. As target speed increases, timing constraints increase and spatial accuracy decreases (e.g., Tresilian et al., 2009). Contradictory results for temporal accuracy have been reported. Some experiments have found timing accuracy decreased (Abernethy & Neal, 1999; Coker, 2006; Park, 2003; Peters, 1997); increased (Long & Vogel, 1998; Peterken et al., 1991; Tresilian & Plooy, 2006; Williams, 2000; Wrisberg et al., 1982); or remain unchanged (Fleury & Bard, 1985) with increased target speed. Three interrelated factors may be important for these disparate findings. Observations that timing errors increase with increased target speed are typically associated with relatively high target speeds, short viewing times, and large biases or constant errors due to late responding at the fastest speeds (e.g., Coker, 2006; Park, 2003; Peters, 1997). In contrast, studies using relatively low target speeds and longer viewing times typically have lower constant errors and timing errors decrease with increased target speed (e.g., Tresilian & Plooy, 2006; Wrisberg et al., 1982).

Increases in spatial constraint also appear to result in greater errors in hitting a moving target. Tresilian et al, (2009) found that when participants were allowed to intercept a target at any point along its path, there is considerable variation in where the interception occurred, and spatial errors in hitting the target were reduced compared to when the point of interception was specified (Tresilian et al., 2009). Similarly, increasing spatial constraint by decreasing the aperture the hand had to move through to intercept the moving target resulted in systematic

57

increases in spatial and timing error in hitting the target.

While the temporal constraint of target speed and the spatial constraint of interception location play a significant role in achieving interception accuracy, less is known about how these two constraints are associated with the gaze control strategy. In Experiment 1, gaze control and movement accuracy were examined in constrained and unconstrained target interception under variations of target speed. Target speeds were relatively low and ranged from speeds easily followed by pursuit eye movements to speeds requiring anticipatory saccades. In constrained target interception the interception point was specified, constraining the performer spatially and temporally. In unconstrained interception the moving target could be intercepted at any point along the targets path. Outcome accuracy, eye fixation time, and POG were the data of interest.

Consistent with previous research (e.g., Tresilian et al., 2009) it was anticipated that increased time constraints and faster target speeds would result in greater absolute and variable spatial errors in hitting the moving target. Increased spatial constraint by specifying the point of interception was also expected to increase absolute and variable spatial errors (Tresilian et al., 2009). Timing errors were expected to decrease with increased target speed. It was assumed that specifying the location of interception would result in less variation in the dart's landing location than unconstrained interception.

Regarding eye fixations, I tested whether trials with accurate performance were characterized by longer final fixation times or a longer time spent in fixation during the trial. Finally, I examined participants POG strategy and how target speed and constraining of the interception point influenced POG. I hypothesized that both increased target speed and constraining the point of interception would increase the participant's tendency to look at the interception point rather than at the moving target.

58

Method

Participants

Twenty four right-handed individuals volunteered for the study. Mean age was 28±10 years and 10 participants were female and 14 were male. Participants were students and faculty that had normal or corrected-to-normal vision, were healthy and without any known oculomotor abnormalities and signed an Institutional Review Board approved consent form.

Apparatus

A steel tip dart (26 g, Halex) was thrown by the participants. An 18 cm diameter target was projected onto a 410×120 cm screen using two LCD projectors (1024×768 pixel; 60 Hz; greater than 1000 lumens of brightness). The projectors were attached to tripods with 3-way pan/tilt heads and positioned at the same height, orientation, and distance from the screen. The zoom was adjusted so that the height of the projected image was the same for both projectors. The tripod heads were adjusted so that the projectors were level with respect to the ground and so that the images from the right-hand edge of the left projector and left hand edge of the right projector were perfectly aligned. Smooth target motion was accomplished at the intersection between projected images by playing two identical video clip 2048 pixels in width. The left projector showed pixels 1 to 1024 and the right projector pixels 1025 to 2048 (see Figure 2). The alignment of two screens was confirmed by projecting a still image of the 18 cm diameter target at pixels 979 to 1069 and confirming that the target was centered on the screen, was 18 cm in diameter and was not distorted.

Eye movement data were recorded using a pupil and corneal reflection system (Applied Science Laboratories Series 5000 Head Mounted Eye Tracker). The system was mounted on a helmet worn by the participant. A camera recorded an image of the eye exposed to infrared light.

59

The line of gaze was determined using the location of the pupil and corneal reflection. An external scene camera was mounted on the helmet pointing outward to show the participant's view. The POG on the screen plane was available on a video monitor and recorded by video recorder (JVC, Japan, Model SR-VS30). The system sampled at 60 Hz, and the raw eye position data was exported to ASL Eye-Trac 6000 software for analysis.

A force transducer was mounted on a wood extension (8.5×60 cm) attached to a tripod to measure the time of movement initiation. A second transducer was attached to the participant's thumb to indicate the time of dart release. A microphone (Sony, Japan, Model DCR-TRV520) was placed behind the dartboard to determine the time of dart landing and to terminate target motion on the video clip. A millisecond timer (Lafayette, Model 54035A) was used to determine movement and flight time. A meter rule was used to record dart landing location in reference to the target to the nearest 0.5 cm.
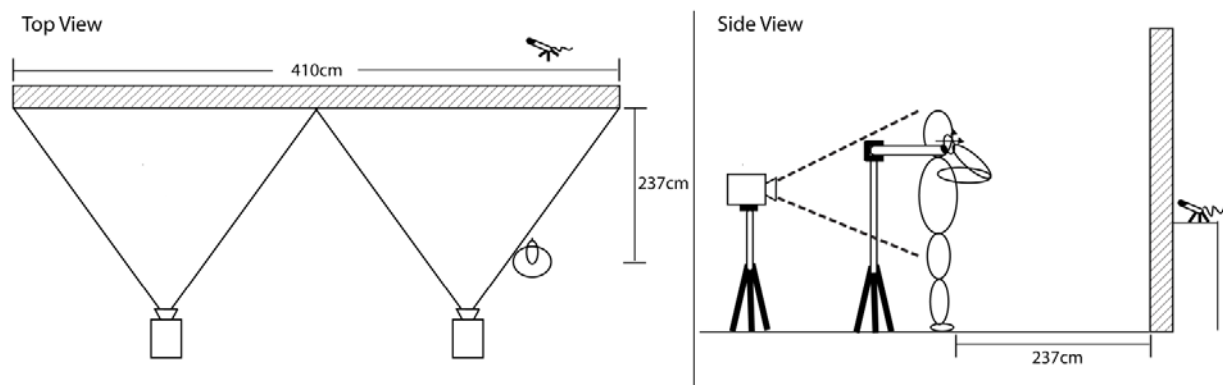

Figure 2. Top and side view of the experimental set-up.

Procedures

Participants performed 15 pretest trials using a fixed stationary target (18 cm diameter) 2.37 m away at a height of 1.55 m from the ground. After completing the pretest the eye-tracking system helmet was put on the participant. Calibration was performed using a nine-point grid

projected on the screen directly in front of the participant. The force transducer was attached to the participant's thumb.

Participants were assigned to one of two groups, and either attempted to intercept the moving target anywhere along the screen (non-fixed interception point, NO-FIP) or when the target overlapped with a fixed crosshair (fixed interception point, FIP). The fixed interception point was represented by a yellow crosshair (18 cm in length) projected on the screen 307.5 cm from the target start. The crosshair appeared at the same time as the moving target and the center of the crosshair and the moving target were at the same vertical level.

The participant stood so that their midline was 100 cm from the right end of the screen. The distance from the participant to the screen was 2.37 m. The participant's task was to throw the dart and intercept the center of the moving target. The target appeared at the left edge of screen at a height of 1.55 m from the ground and moved horizontally toward the right hand edge of the screen. The target stopped when the dart contacted the screen.

Throws were initiated from a full elbow flexion position with the upper arm parallel to the ground. The elbow was pointed toward the target and the hand was directly above the shoulder. The force transducer and tripod assembly was positioned so that the hand rested lightly on the transducer in this position. Participants were instructed to make a single discrete elbow extension, that is, without stopping between moving the hand away from the transducer and the release of the dart.

Three target speeds, 732, 1464, 2193 mm/s (corresponding to 14, 27, or 40 ° of visual angle per second) were used. Twenty trials were performed at each target speed with 20 s between trials. Target speeds were blocked and the order was counterbalanced. There was a 2 min rest between blocks. Participants viewed one trial of target motion before the start of the

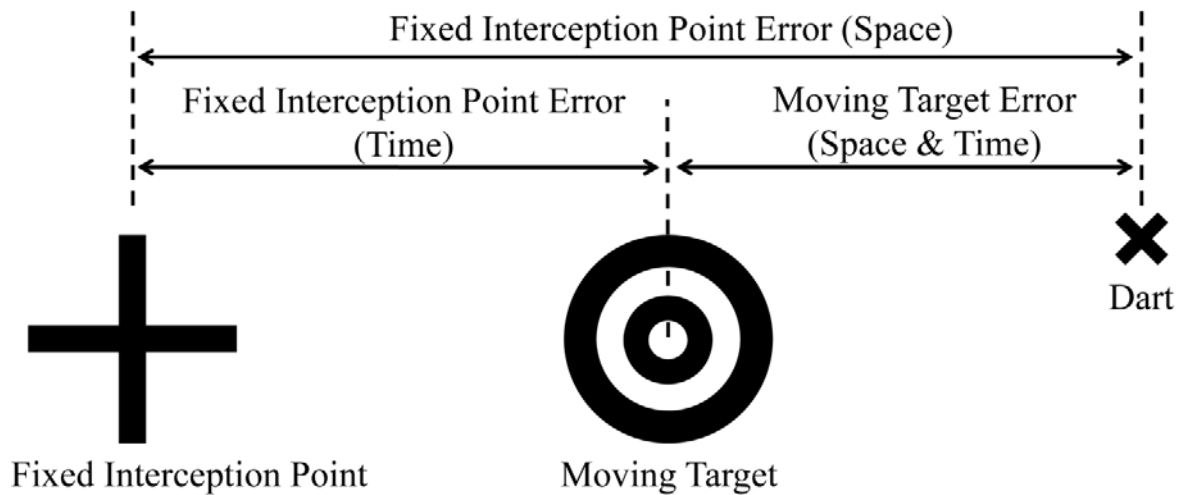experiment, with a randomly determined target speed.

Figure 3. A pictorial definition of spatial and temporal errors relative to the fixed interception point and moving target in FIP condition.

Data Analysis

    Performance. Horizontal spatial error was measured from the dart landing location to the center of the moving target (see Figure 3). Constant error (CE), the signed deviation between the dart landing position and the target center; absolute error (AE), the absolute deviation between the dart landing position and the target center; and variable error (VE), the standard deviation of the individual CE scores, were computed. Darts landing to the right of the moving target resulted in positive constant spatial errors. Temporal error scores for each trial were obtained by dividing spatial constant error by the target speed for the condition. CE, AE, and VE of time were analyzed. I also measured spatial variability in laboratory space. That is, I measured the standard deviation of the dart landing location from the edge of the screen independent of the position of the moving target (Tresilian et al., 2009). The variability in laboratory space in the NO-FIP group is the same as variable error in hitting the fixed interception point (FIP group). Flight time was

defined as the time interval between dart release and dart landing (measured using the microphone placed behind the screen). Trials where the dart landed within the range of the moving target in the NO-FIP group were considered accurate trials (horizontal absolute error < 9 cm). For the FIP group, accurate trials were defined when the dart landed on the overlapped area of the fixed interception point and the moving target (AE < 9 cm for both fixed interception point and moving target).

Eye movement. The number of fixations, total fixation duration for the trial, and final fixation duration were calculated. A fixation was defined as an eye movement of less than 1° of visual angle for 100 ms or longer. The number of fixations was the total number of fixations starting with target motion and ending with the fixation initiated before the start of arm motion. This last fixation was defined as the final fixation.

The POG with reference to the moving target was determined at 14 equally spaced horizontal target positions. This was accomplished by viewing the video-taped recording of the external eye-tracker camera output and the superimposed crosshair representing POG within the visual field. The 14 equally spaced target positions were obtained by determining the POG at the initiation of target motion, and then for every 12, 6, or 4 frames for the slow, medium, and fast target speeds respectively. The POG for each of the 14 target positions was coded based on whether the POG was on the target start position, behind the target (left of target), on the target, ahead of the target (right of target), or on the dart landing site.

Statistical Analysis. The effect of target speed and interception point on spatial and temporal accuracy, dart flight time, and total fixation duration was analyzed using a two-way mixed design analysis of variance. Speed was a within subject factor and interception point was a between subject factor. In the case of violations of the sphericity assumption, F values were

adjusted with the Greenhouse-Geisser procedures. Chi-Square was used to analyze the frequency of eye fixations and Hierarchical Log-linear nonparametric analysis was used to examine POG. In the POG analysis the impact of target speed, target segment, POG location, and interception point was examined. Final fixation times and total fixation times were compared for accurate and inaccurate trials using a paired t-test (two-tailed). A paired t-test (two-tailed) was also used to compare variability about the moving target with variability in laboratory space, and also pretest variability with laboratory space variability. The alpha level for all statistical tests was .05.

Results

Performance

In order to examine the influence of time and space constraints on performance, spatial and temporal accuracy in hitting the moving target was examined. There was a significant influence of target speed on all accuracy measures (see Table 2). There was a significant aiming bias as measured by mean CE for both space $[F(2,44) = 26.40, \eta_P^2 = 0.545, p < .01]$ and time $[F(1.22,26.82) = 8.99, \eta_P^2 = 0.290, p < .01, \varepsilon = 0.610]$. Darts tended to land farther behind the target and too late in time as target speed increased. Increased target speed also resulted in lower spatial accuracy as measured by mean AE $[F(2,44) = 23.64, \eta_P^2 = 0.518, p < .01]$, but temporal accuracy $[F(2,44) = 31.18, \eta_P^2 = 0.586, p < .01]$ was greater at faster target speeds. Larger spatial variability as measured by mean VE $[F(1.57,34.90) = 18.78, \eta_P^2 = 0.461, p < .01, \varepsilon = 0.793]$ and smaller temporal variability $[F(2,44) = 64.53, \eta_P^2 = 0.746, p < .01]$ were found as target speed increased. There was also a significant main effect of fixed interception point for spatial accuracy (AE) $[F(1,22) = 5.11, \eta_P^2 = 0.189, p < .05]$, temporal accuracy (AE) $[F(1,22) = 5.80, \eta_P^2 = 0.209, p < .05]$, and variability (VE) of space $[F(1,22) = 13.06, \eta_P^2 = 0.373, p < .01]$ and time $[F(1,22) = 13.44, \eta_P^2 = 0.379, p <$

64

.01]. Greater accuracy and less variability were observed when the point of interception was not specified (NO-FIP group).

Spatial variability in laboratory space provides an indication of how greater time constraints brought about by faster target speeds, and how space constraints associated with a fixed interception point, influenced variation in where interception occurs in space. We examined whether less stringent constraints resulted in greater variation in interception location. The spatial variability in laboratory space did not change significantly as target speed increased or with the presence or absence of a fixed spatial target. A comparison of variability in laboratory space and variability about the moving target indicated that laboratory space variability was significantly lower $[t(11) = 6.05, \ p < .01]$. Finally, spatial variability of throws during the pretest was significantly smaller than spatial variability in laboratory space for both non-fixed (NO-FIP) $[t(11) = -7.09, \ p < .01]$ and fixed (FIP) interception point $[t(11) = -3.75, \ p < .01]$ groups. The main effect of target speed on flight time was statistically significant $[F(2, 44) = 12.71, \eta_P^2 = 0.366, p < .01]$. Participants threw faster at faster target speeds. Flight times were 325.15, 317.45, and 296.1 ms for the slow, medium, and fast target speeds, respectively.

Eye Movements

Eye movement fixation characteristics and POG provide information regarding the eye movement strategies adopted by participants. The number of fixations decreased as target speed increased $[\chi^2(2) = 9.33, \ p < .01; 11.05, 4.05,$ and 2.2 for the slow, medium, and fast target speeds, respectively]. Total fixation duration $[F(2, 44) = 596.78, \eta_P^2 = 0.964, p < .01; 3.2,$ 1.43, and 0.89 s for the slow, medium, and fast target speeds, respectively] also decreased as target speed increased. These effects appear to be largely due to differences in target motion duration. The percentage of time spent in fixation did not differ among target speeds F < 1. There

Table 2 *Summary of error scores (±standard deviation) as a function of target speed and interception point*

Variable\Speed		Slow (792 mm/s)		Medium (1464 mm/s)		Fast (2193 mm/s)	
		NO-FIP	FIP	NO-FIP	FIP	NO-FIP	FIP
Spatial (mm)	CE*	19.1±45.8	-3.9±84.0	-52.8±43.5	-69.4±51.4	-104.0±61.9	-80.2±40.2
	AE*+	79.1±24.1	110.2±41.3	111.5±25.1	140.6±40.2	144.2±42.5	174.0±64.8
	VE*+	87.7±19.0	121.9±64.8	122.4±26.3	158.5±39.9	130.5±24.8	188.1±68.1
Temporal (ms)	CE*	26.1±62.6	-5.6±114.7	-36.0±29.7	-47.4±35.1	-47.0±28.2	-36.6±42.4
	AE*+	108.1±32.9	150.1±56.7	76.1±17.1	96.1±27.4	65.7±19.3	79.4±29.5
	VE*+	119.8±25.9	166.3±43.5	83.6±17.9	108.3±27.2	59.5±11.3	85.8±31.0
Lab Space (mm)	VE	96.3±26.5	95.9±25.3	97.2±19.6	96.0±47.7	103.4±22.3	88.6±51.7
Pre-test (mm)	VE	59.4±23.5	59.0±18.2				

Note. NO-FIP = no Fixed Interception Point. FIP = Fixed Interception Point. *$p < .05$ target speed; +$p < .05$ interception point.
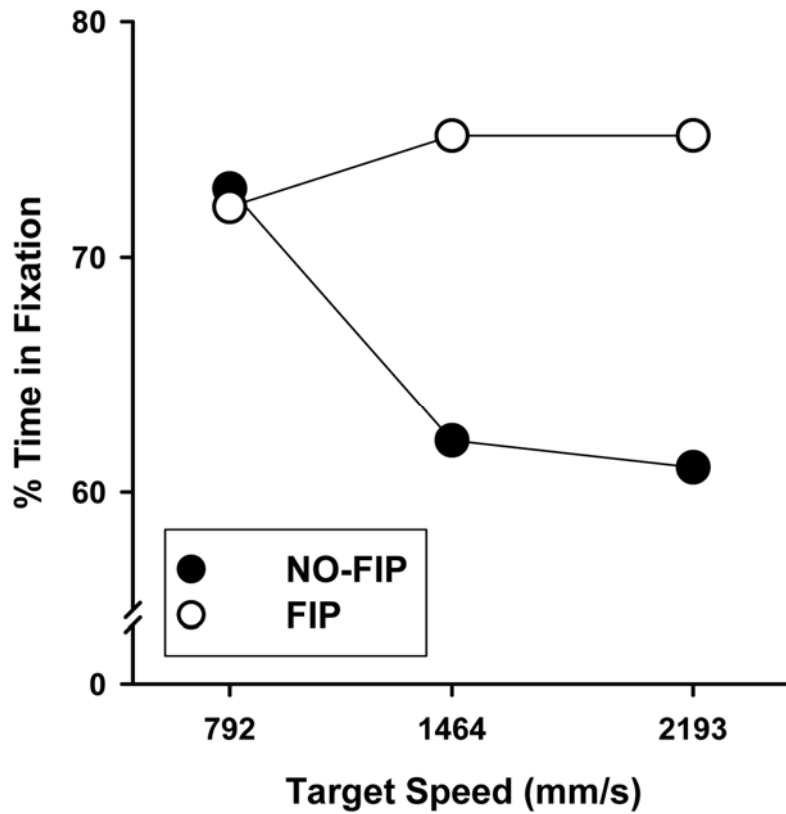
Figure 4. Interaction between target speed and percentage time spent in fixation.

was, however, a significant interaction between target speed and interception point for the percentage of time spent in fixation $[F(2, 44) = 3.72, \eta_P^2 = 0.145, p < .05]$ (see Figure 4). Participants spent a similar percentage of time in fixation across target speeds when the interception point was specified. When participants were able to intercept the target at any point along the target path, they spent a low percentage of time in fixations at the two fastest target speeds. Final fixation times (.38 and .36 s) and total fixation times (1.85 and 1.82 s) did not differ between accurate and inaccurate trials, respectively.

POG

Due to technical difficulties POG data were only available for 5 participants in NO-FIP
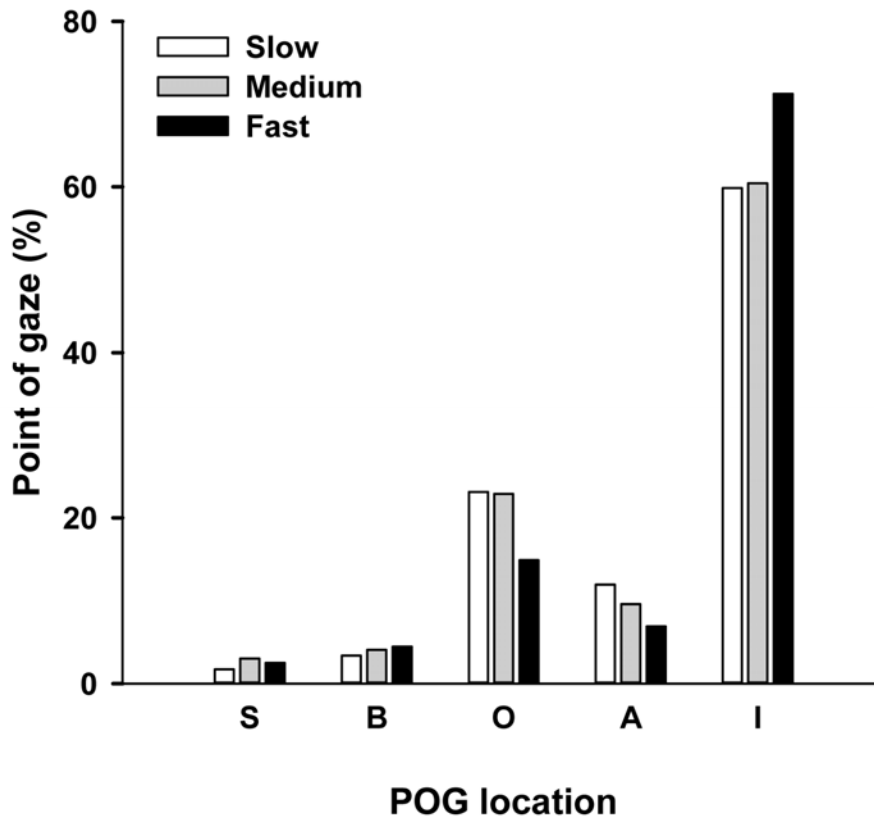
Figure 5. Interaction between POG location and target speed (S = start; B = behind target; O = on target; A = ahead of target; I = interception point).

group. In FIP group, all twelve participants' video recordings were analyzed. POG data were segregated into four moving target ranges: segments 1 to 4, 5 to 8, 9 to 12, and 13 and 14. During the last segment the moving target and the final interception area overlapped momentarily. When this occurred and eye fixations coincided with both points, the data were coded as a fixation on the final interception area. Statistical analysis revealed that POG was not evenly distributed among the five possible gaze locations $[\chi^2(4) = 3124.78, \ p < .01]$. Participants showed a tendency to look mostly at the anticipated dart landing site and this tendency increased with target speed as indicated by a significant interaction between POG location and target speed $[\chi^2(8) = 68.65, \ p < .01]$ (Figure 5). POG also interacted with target

segments $[\chi^2(12) = 258.60, \; p < .01]$ and interception point $[\chi^2(4) = 65.02, \; p < .01]$. There was also a significant 3-way interaction among POG, target segment, and interception point $[\chi^2(12) = 172.41, \; p < .01]$. As can be seen in Figure 6, participants looked at the anticipated dart landing site more frequently, and looked at the moving target less frequently as the target approached the end of the display (segment 14). This was especially the case for the fixed interception point condition.

Figure 6. 3-way interaction between segment, POG location, and interception point (S = start; B = behind target; O = on target; A = ahead of target; I = interception point).

Discussion

       Participants were asked to throw a projectile to intercept a target that moved horizontally along a plane perpendicular to the participant. While a number of studies have examined eye movement control with a fixed target and with targets approaching the performer, few studies have examined interceptive target aiming. The experiments allowed for an examination of visual gaze and spatial and temporal accuracy as a function of target speed and constraining the point of

interception.

Spatial and temporal accuracy

Target speed and interception constraint significantly contributed to the spatial and temporal accuracy of performance. As target speed increased, creating greater time constraints, spatial accuracy relative to the moving target decreased and timing accuracy increased. These findings are consistent with previous evidence for the interdependent relationship between spatial and temporal accuracy in interceptive tasks (Tresilian et al., 2009). Whether increases in target speed result in increases or decreases in timing accuracy depends on a number of factors. For experimental conditions that cause a large increase in timing error bias, when target speed increases timing accuracy decreases. Timing error bias can occur with very high target speeds (Peters, 1997), short viewing times (Park, 2003) and/or long movement times in interception tasks (Coker, 2006; Peters, 1997). Under these conditions performers tend to respond late leading to a large timing error bias and low timing accuracy. When participants are given longer viewing times and time to respond, bias tends to be small and timing accuracy increases with increases in target speed. Increased spatial error and decreased timing error with increases in speed are consistent with findings from experiments examining movement accuracy using a space-time accuracy paradigm (Newell, Carlton, & Kim, 1994; Newell et al., 1980).

Constraining the point of interception resulted in increased spatial and timing error in hitting the moving target but, contrary to our assumption, laboratory space variability was independent of interception point constraint. Whether participants were specifically told where in space to contact the target, or were told that they could contact the target at any location along the targets path, they were equally consistent in where they threw the dart. We also found that variability in laboratory space was smaller than variability about the moving target and again this

70

was the case whether or not interception was constrained. These findings support the notion that the interception location is specified in advance of movement initiation and is preserved over trials under the same conditions. These results are contrast to Tresilian et al. (2009) who found that unconstrained target interception was characterized by greater variability in the location of interception than variability in errors in hitting the moving target. We expect that the differences in our and Tresilian et al. findings are related to task constraints of far target aiming. The accuracy of projecting an object to a far target is going to be influenced by the projection distance. An examination of the spatial location of dart landing suggests that participants attempted to minimize the projection distance by intercepting the moving target directly in front of them.

Gaze control characteristics

The gaze analysis focused on the characteristics of visual fixations and POG during target motion. Previous studies have shown that duration of the final fixation played an essential role in determining the quality of performance (e.g., Behan & Wilson, 2008; Panchuk & Vickers, 2006; Vickers, 1996; Williams et al., 2002). The gaze behavior data showed that increased target speed was related to fewer fixations and shorter total fixation durations but this appears to be mostly a function of the shorter duration of target exposure at faster target speeds. The percentage time spent in fixations did not differ among target speeds. Target speed also influenced POG. Participants spent a greater proportion of time looking at the intended interception point at higher target velocities. This finding is in contrast with observations in cricket batting where no simple relationship between ball projection speed and visual gaze strategies was found (Croft, Button, & Dicks, 2010). This difference in findings may be a function of the much larger range of target speeds in the present study or may be related to the

71

use of a blocked versus random presentation of target speeds.

Accurate trials did not tend to have longer final fixations or longer total fixations than inaccurate trials. We did examine whether performers who were more accurate on the pretest had longer final fixations than less accurate performers, and again there were no observable differences in final fixations times. These findings are inconsistent with previous research using fixed targets (Behan & Wilson, 2008; Janelle et al., 2000; Panchuk & Vickers, 2006; Vickers, 1992, 1996; Vickers et al., 2000; Williams et al., 2002). However, it should be noted that none of the participants had practice at throwing darts at a moving target and we were reluctant to classify participants as being skilled or unskilled at the task.

When the visual target is moving toward the performer and must be struck, a number of studies have emphasized that a stable eye position is associated with performance accuracy. Rodrigues et al. (2002), for example, found that experts stabilize the eye and head as the arm moved to stroke a table-tennis ball and the stabilization lasted for about 100 ms up until a point 30 ms before ball-bat contact. Furthermore, Lafont (2008) found that experts in tennis maintain a stable head position and fixated in the direction of the impact point during groundstrokes. Because the ball moves across the retina once the head and eyes are fixated, increased sensitivity to ball motion through peripheral vision may enhance the process of obtaining information from the ball's final trajectory (Rodrigues et al., 2002).

In contrast to an eye movement strategy that reduces the accumulated POG and target position error (Klam et al., 2001) participants tended to gaze at the intended interception point and this was enhanced by the presence of a specified interception point. Fixating on the intended interception point may be beneficial for movement accuracy and may also facilitate visual perception of target motion. In pointing, both head position and eye position influence aiming

72

accuracy (Henriques, 2002; Rossetti, Tadary, & Prablanc, 1994). Looking at the moving target and throwing to a position some distance ahead of the point of gaze may reduce throwing accuracy. The longer the projectile flight time and the faster the target speed, the greater the horizontal distance between the target position at movement initiation and the target position at interception. In general information regarding the motion of a target is available independent of whether the performer visually tracks the moving target. Accurate timing, for example, was not influenced by whether the performer visually tracks the target or fixates their vision somewhere near the interception point (Long & Vogel, 1998; Peterken et al., 1991). However, tracking the target may minimize optical flow information when the motion takes place against a uniform background as was the case in the present experiment. Optical flow information may be essential when the performer must estimate the position of a moving target at some future time.

One possible reason for the discrepancy between our and previous research is that the principal gaze direction required in our experiment was horizontal, whereas in previous studies the targets were stationary (e.g., basketball free-throw, billiard, dart throwing, soccer penalty kicks, or rifle shooting), or when moving targets were used, followed a head-on approach (e.g., table-tennis forehand stroke, ice-hockey goaltending, or volleyball serve receive). In the case of stationary target aiming or oncoming target interception, a smaller range of eye motion is often required and thus the main components in gaze control (e.g., fixation, smooth pursuit, or saccades) may be quite different from tracking a horizontally moving target over a long path. For example, it has been suggested that visual control strategies may be different in cases where an object motion radiates out from a central point (radial motion) and where the target moves along a plane (lamellar motion) (Bennett et al., 2010; Long & Vogel, 1998).

For moving targets, depending on the constraints imposed by the task, head and eye

movement control may vary. For example, due to the time delay associated with the movement of the effector and the projectiles' flight duration in interceptive aiming, the intended interception point will be ahead of the moving target position at movement initiation. Under these constraints performers tend to gaze on the interception point. In contrast, direct tracking and aiming on the target may be optimal in tasks such as in skeet shooting where the movement execution time and flight time are very small. Therefore, developing a coordinated eye and head motion toward the critical spatial reference, rather than trying to continuously foveate the target might be a key factor for successful aiming performance.

EXPERIMENT 2. CHARACTERISTICS OF TARGET MOTION AND VISUAL SEARCH

STRATEGY

Introduction

People, in general, tend to look at the moving object that they intend to intercept. When the moving object cannot be followed using pursuit eye movements and/or when the object motion characteristics are well internalized (e.g., Benguigui & Bennett, 2010; Land & McLeod, 2000), the gaze location tends to be switched onto the predicted interception location. As such, interacting with a moving object in a highly predictable situation allows the performer to use anticipatory processes for control of the oculomotor system as well as the planning and execution of the motor response. The use of smooth pursuit and saccadic components in voluntary visual tracking is dependent on the predictability and the over-all configuration of the target's trajectory (Collewijn & Tamminga, 1984; Kowler & Steinman, 1981; Mrotek & Soechting, 2007). In addition, success rate and spatial accuracy in interceptive hitting are influenced by the availability of advance target motion information (Marinovic et al., 2010). A number of parameters have been manipulated to decrease predictability of target motion including movement direction and amplitude (Marinovic et al., 2008, 2010), target motion path (Mrotek & Soechting, 2007), and target speed change (Teixeira et al., 2006). However the associations of these parameters with eye movement control is not well understood.

Anticipation of future events is one of the essential components for the accurate interception of a moving target. Given the inherent sensory and motor delays and the time required to move the effector to the target, the anticipation process must compensate for the delays. Two types of anticipation are necessary. Perceptual anticipation is required based on the target motion characteristics such as target velocity and direction. Receptor anticipation is

75

required to time the initiation of the movement (Poulton, 1954). These predictions are dependent upon how much information is available and when the exact point in time the information is accessed by the perceptual system (Williams et al., 1999). As such, anticipation and action is incorporated together into the control of interceptive action.

Previous research suggested three types of information as being important for anticipation. Visually sensed concurrent target motion characteristics (Port et al., 1997; Zago et al., 2009), expectations based on the experience from previous trials (de Lussanet et al., 2001; Soechting et al., 2005), or an internal model of the object's dynamic property (Hayhoe et al., 2005) influence the motor response. Previous studies have shown that kinematics and accuracy of interceptive action are influenced by advance knowledge such as pre-cueing of spatial and temporal characteristics of target motion (Morice et al., 2010; Rosenbaum & Kornblum, 1982; Tijtgat et al., 2010) as well as by information from previous experience (de Lussanet et al., 2001). However, there have been few investigations into whether prior knowledge about the temporal characteristic of target motion influences the visual search pattern.

Experiment 2 was designed to address whether advance knowledge of target speed presentation, as well as the predictability of the target motion, influences gaze control strategy and interception accuracy. Gaze control and interception accuracy was examined under known and repeated target speed presentation versus unknown and random presentation conditions. Target speed and spatial path were also varied from highly predictable to less predictable patterns. It was hypothesized that participants would tend to look at the self-selected target interception point rather than at the moving target but this tendency would decrease when the target motion trajectory and speed unpredictably varies. Target speed change would result in increased use of pursuit tracking, rather using the performer-determined predictive strategy. It

was also hypothesized that participants would increasingly use smooth pursuit eye movements to track the moving target in the slow speed. With respect to interception accuracy it was predicted that as target motion becomes less predictable the spatial and temporal interception accuracy would significantly decline.

Method

Participants

Twenty four volunteers (mean age = 28±4 years) were recruited for the study. 7 participants were female and 17 were male. One participant in each gender was left-handed. Participants were required to have normal or corrected-to-normal vision and be healthy and without any known oculomotor abnormalities. Participants provided informed consent and the procedures were approved by the Institutional Review Board.

Apparatus

The apparatus, including the eye-tracking unit, video recording, and dart throwing setups were identical to those described in Experiment 1. In Experiment 2, the participant's midline was aligned with the horizontal center of the screen. POG with respect to the observed scene plane was acquired using a magnetic head tracker (Ascension Flock of Birds; Ascension Technology Corporation, VT, USA). Head position and orientation in 3-dimensional space were measured by two components, the magnetic field transmitter and receiver (1.8 mm RMS accuracy). The head tracker measured where the receiver was in real space based on the distance and orientation of the center points of the two components. The transmitter was located 75 cm behind the participant and the receiver was attached on the helmet worn by the participant. Eye-head Integration software (Applied Science Laboratories, MA, USA) was used to calibrate the spatial relationship between the transmitter and the scene plane established by three corner points of the

rectangular scene boundary. Eye and head position data were integrated and POG was recorded on the scene plane in the unit of millimeters.

Procedures

The general procedures were also similar to Experiment 1 except that the target presentation order and the target motion characteristics were manipulated. Interception location was not constrained in any condition. Each participant completed four conditions of target presentation that varied in the predictability of target motion. Each of the four target motion predictability conditions were completed at two average horizontal target speeds (915 mm/s or 17 °/s visual angle (Slow) and 2011 mm/s or 37 °/s visual angle (Fast)). The target moved from left to right. Each target speed was repeated 15 times for a total of 30 trials for each condition. The total data set was 15 trials × 2 average target speeds × 4 target predictability conditions for a total of 120 trials per each participant. Participants were shown each target speed at the beginning of each condition. In the blocked order condition, each target speed was shown before starting each speed block. The four visual presentation conditions are described below in the order of most predictable target motion to least predictable.

Blocked order constant speed (B). Two average horizontal target speeds were presented in blocked order. The order of target speeds was counter balanced between the participants. The target moved on a horizontal path and the speed was constant.

Random order constant speed (R). The target speeds used in the blocked order condition were also employed in random order condition. Target speed was randomized and varied from trial to trial. Like the Blocked order constant speed condition the target path was horizontal and target speed was constant.

Random order random path (RP). In the random order random path condition vertical

78

target motion was added. Horizontal velocity within a trial was constant, similar to the blocked and random order constant speed conditions. The introduction of vertical motion caused target speed to vary during the trial. For both slow and fast horizontal target velocity conditions five different target paths were used. The vertical component consisted of the sum of four non-harmonic sine waves of different amplitudes, frequencies, and phases (e.g., Collewijn & Tamminga, 1984) (see Table 3 and Figure 7). The horizontal component was not manipulated so that the rate the target changed its position rightwards (i.e., horizontal velocity) was constant over the target path. Each target path profile was repeated 3 times at each target speed. Target motion duration and average horizontal target speed were equal across target speed profiles or paths. The order of target speeds and target paths was randomized.

Random order random horizontal speed (RHS). Lastly, in the random order random horizontal speed condition, the target followed a straight horizontal path as in the constant speed condition but target speed varied based on pseudo-random speed profiles. The speed profile of target motion was constructed using the sum of sines (see Table 3 and Figure 7). Horizontal target velocity was always greater than zero so that the target always advanced rightwards, neither stopped instantly nor moved backwards (i.e., leftwards). Within each average target speed, however, target motion duration and average target speed were equal across target speed profiles. Five different pseudo-random target speed profiles were repeated 3 times at each speed. The order of presenting target speeds and speed profiles was randomized.

Data Analysis

Performance & Eye Movement. The analyses regarding interception accuracy and eye fixation characteristics were identical to Experiment 1. POG with reference to the moving target was analyzed for the time period from the target motion onset to the dart landing at every 1/60
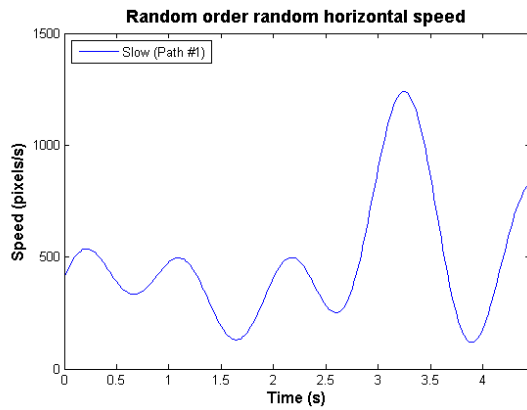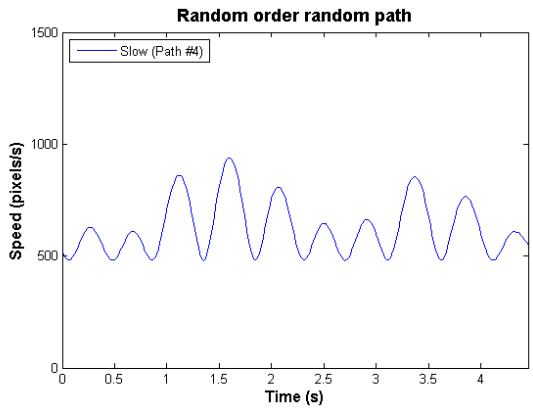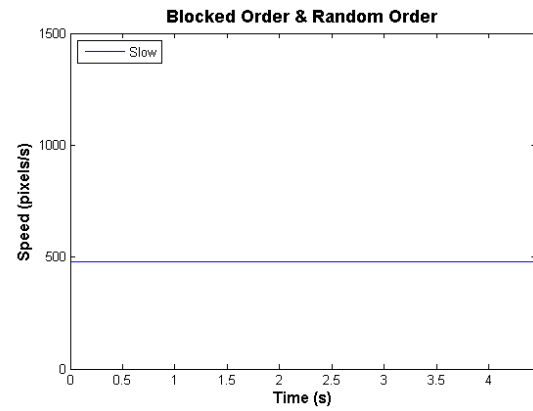
Table 3 *Target trajectory parameters*

	Random order random path (RP)							Random order random horizontal speed (RHS)						
Speed	Trajectory	Parameter	Sines in the y (vertical, positive up)				Speed	Trajectory	Parameter	Sines in the x (horizontal, positive right)			
			1	2	3	4				1	2	3	4
Slow	1	A	0.48	0.96	2.11	2.11	Slow	1	A	6.37	2.62	1.94	1.44
		F	1.23	1.11	1.00	0.74			F	0.21	0.52	0.70	0.95
		P	-30	-15	60	45			P	-30	-60	-90	-120
	2	A	0.48	0.96	2.11	2.51		2	A	0.28	0.44	0.80	1.40
		F	1.39	0.95	0.64	1.36			F	2.40	0.87	0.54	1.06
		P	0	30	60	-15			P	30	45	60	0
	3	A	0.68	1.16	1.42	1.70		3	A	0.29	0.41	0.94	1.19
		F	1.98	1.22	0.74	0.69			F	2.75	1.55	1.27	0.73
		P	0	30	45	-60			P	45	60	90	-30
	4	A	1.72	1.88	2.00	2.07		4	A	5.56	2.53	0.96	0.75
		F	1.17	1.05	0.64	0.12			F	0.15	0.34	0.89	1.13
		P	-15	-45	-60	0			P	0	30	60	90
	5	A	2.07	1.76	1.08	0.32		5	A	2.97	2.13	0.59	0.76
		F	1.33	1.02	0.61	0.15			F	0.21	0.33	0.89	1.12
		P	120	45	30	-15			P	-15	-30	60	90
Fast	1	A	0.48	0.96	2.11	2.11	Fast	1	A	0.48	0.80	1.92	1.48
		F	2.68	1.44	1.07	0.30			F	4.40	0.87	1.03	2.06
		P	0	30	60	90			P	30	45	60	0
	2	A	0.68	1.16	1.42	1.70		2	A	0.69	0.81	1.34	1.58
		F	3.68	2.02	1.14	0.69			F	2.25	1.55	1.27	0.73
		P	0	30	45	-60			P	45	60	90	-30
	3	A	1.72	1.88	2.00	2.47		3	A	5.56	2.53	0.96	0.75
		F	1.87	1.05	0.64	0.12			F	0.15	0.34	0.89	1.13
		P	-15	-45	-60	0			P	0	30	60	90
	4	A	2.87	1.76	1.08	0.32		4	A	6.37	2.62	1.94	1.44
		F	1.68	1.21	0.61	0.15			F	1.01	0.62	0.70	0.95
		P	120	45	30	-15			P	-30	-60	-90	-120
	5	A	2.07	1.36	1.48	0.72		5	A	6.37	2.62	1.94	1.44
		F	2.00	1.46	0.77	0.14			F	1.21	0.92	0.80	1.15
		P	100	75	50	-30			P	0	5	-15	135

Note. $x_t (or\ y_t) = A_1 \sin(\omega_1 t + \varphi_1) + A_2 \sin(\omega_2 t + \varphi_2) + A_3 \sin(\omega_3 t + \varphi_3) + A_4 \sin(\omega_4 t + \varphi_4)$, where $x_t (or\ y_t)$ denotes the horizontal (or vertical) target position at time t. The parameter A, F, and P denotes the amplitude (°), frequency (Hz), and phase (°), respectively.
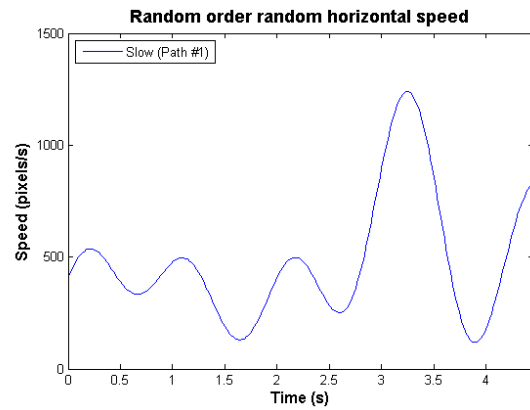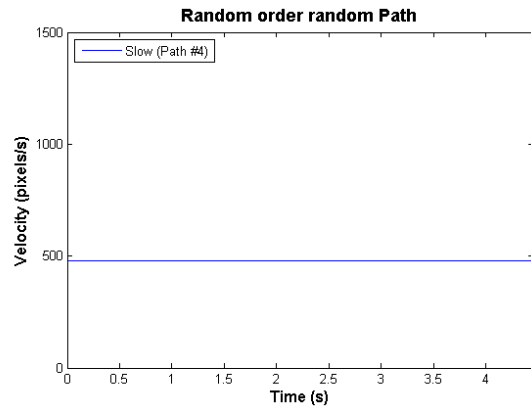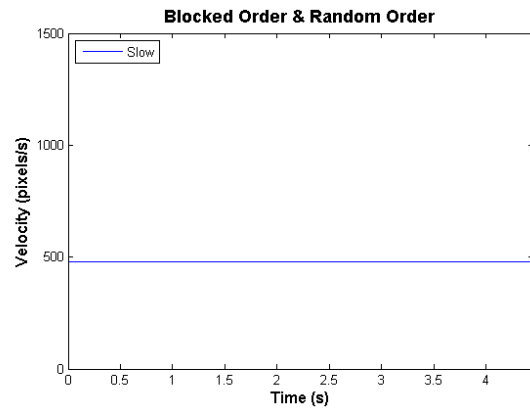
Figure 7. Speed and horizontal velocity profile of each target predictability condition. Left: Target speed profiles. Target speed was either constant (Blocked and Random order constant speed condition) or randomly varied (Random order random path and Random order random horizontal speed condition). Right: Horizontal velocity profiles. Horizontal velocity was constant except for the Random order random horizontal speed condition. Average horizontal velocity was the same for all conditions.

second. This was attained by comparing spatial coordinates of POG on the scene plane with those of the target center. The relationship between POG and target center was examined using 4 equally spaced spatial-temporal ranges. The time from target motion onset (0%) to dart landing (100%) was equally divided into 25% time intervals. In the Blocked order constant speed, Random order constant speed, and Random order random path conditions the horizontal speed was constant and the four interquartile ranges represented four equal size spatial segments. In the Random order random horizontal speed condition the spatial segments varied slightly because horizontal speed was not constant. In order to code the POG for the five locations used in Experiment 1, 5° of visual angle range was used as the criteria. This corresponded to 34 cm on the projection screen. The POG was coded based on whether the POG was on the target start position (5° from the target location at motion onset), behind the target (left of the target center by more than 2.5°), on the target (within 2.5° of target center), ahead of the target (right of the target by more than 2.5°), or on the interception area (within 2.5° the target or dart landing location) in each trial. All POG were identified by the above criteria.

Statistical Analysis. The dependent measures and statistical analyses were similar to those described in Experiment 1. Because participants performed under four different target motion predictability conditions, a 2 average target speed $\times$ 4 target motion predictability ANOVA with repeated measures on both variables was applied. In the case of violations of the sphericity assumption, F values were adjusted with the Greenhouse-Geisser procedure. Significant main and interaction effects were further analyzed using Bonferonni post-hoc tests. A paired t-test (two-tailed) was used to compare variability about the moving target with variability in laboratory space, and also pretest variability with laboratory space variability. Chi-Square was used to analyze the frequency of eye fixations and Hierarchical Log-linear nonparametric

analysis was used to examine POG. In the POG analysis the impact of target speed, target segment (i.e., interquartile range), POG location, and target predictability condition was examined. Final fixation times and total fixation times were compared for accurate and inaccurate trials using a paired t-test (two-tailed). The level of significance for all statistical tests was set at p < .05.

Results

Performance

Moving target interception accuracy was assessed with regards to target speed and target motion predictability. In general, there was a significant main effect of both target speed and target motion predictability on accuracy measures (see Table 4).

A significant main effect of target speed on aiming bias was observed for both space $[F(1, 23) = 156.04, \eta_P^2 = 0.872, p < .01]$ and time $[F(1, 23) = 108.96, \eta_P^2 = 0.826, p < .01]$. Participants threw the dart slightly ahead of the target when target speed was slow so that interception occurred early, and well behind the target when the target speed was fast. Spatial and temporal aiming bias did not differ among target predictability conditions. However, there was a significant speed $\times$ target predictability interaction for CE space $[F(1.81, 41.65) = 5.46, \eta_P^2 = 0.192, p < .01, \varepsilon = 0.604]$ and CE time $[F(2.02, 46.44) = 4.68, \eta_P^2 = 0.169, p < .01 \ \varepsilon = 0.673]$. Participants aimed ahead of the target, and interception occurred early to a similar extent across target predictability conditions when target speed was slow. In contrast, the aimed location was further behind the target, and late interception timing became increasingly larger, when target motion became less predictable (see Figure 8).

Increased target speed resulted in lower spatial accuracy $[F(1, 23) = 156.04, \ \eta_P^2 = 0.872, \ p < .01]$ but greater temporal accuracy $[F(1, 23) = 19.82, \eta_P^2 = 0.463, p < .01]$ as

measured by mean AE. There was also a significant main effect of target predictability on both spatial $[F(2.16, 49.66) = 55.05, \eta_P^2 = 0.705, p < .01, \varepsilon = 0.720]$ and temporal accuracy $[F(3, 69) = 65.09, \eta_P^2 = 0.739, p < .01]$ again as measured by mean AE. Post hoc comparisons showed that there was significantly greater AE in space and time for Random order random path and Random order random horizontal speed conditions as compared to the blocked and Random order conditions $(ps < .01)$. Further, the Random order random horizontal speed condition showed greater AE in space and time as compared to the Random order random path condition $(p < .01)$. While interception was more accurate in time when target motion was more predictable, there was a significant interaction between target speed and target motion predictability $[F(1.80, 41.57) = 8.90, \eta_P^2 = 0.279, p < .01, \varepsilon = 0.603]$. There was a much greater increase in AE in the Random order random horizontal speed condition with slow versus fast target speeds (see Figure 9).

The main effects of speed and target predictability on spatial and temporal VE were also significant. Spatial VE increased as target speed increased $[F(1, 23) = 16.33, \eta_P^2 = 0.415, p < .01]$ as well as when the target became less predictable $[F(2.14, 49.10) = 81.66, \eta_P^2 = 0.780, p < .01, \varepsilon = 0.712]$. Temporal VE, on the other hand, decreased with increased target speed $[F(1, 23) = 110.52, \eta_P^2 = 0.828, p < .01]$. Variable timing error was fairly constant for the Blocked order constant speed, Random order constant speed, and Random order random path conditions, but increased sharply when the horizontal velocity changed during the trial in the Random order random horizontal speed condition $[F(2.19, 50.47) = 60.87, \eta_P^2 = 0.726, p < .01, \varepsilon = 0.732]$. Post hoc comparisons revealed greater variability in space and time in the Random order random horizontal speed condition compared to all other conditions $(ps < .01)$. Similar to AE, there was a significant interaction between target motion predictability and target

speed for VE of time $[F(2.19, 50.48) = 5.72, \eta_P^2 = 0.199, p < .01, \varepsilon = 0.732]$ (see Figure 9).
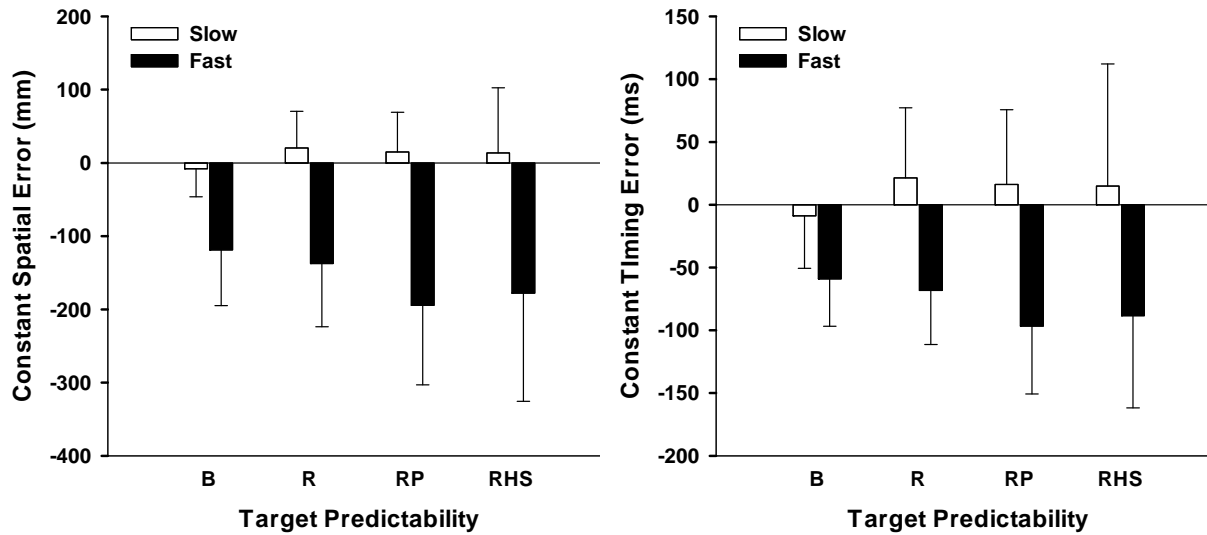

Figure 8. Interaction between target predictability and target speed for constant spatial and timing error (B = Blocked Order Constant Speed; R = Random Order Constant Speed; RP = Random Order Random Path; RHS = Random Order Random Horizontal Speed).

Figure 9. Interaction between target predictability and target speed for absolute and variable timing error (B = Blocked Order Constant Speed; R = Random Order Constant Speed; RP = Random Order Random Path; RHS = Random Order Random Horizontal Speed).
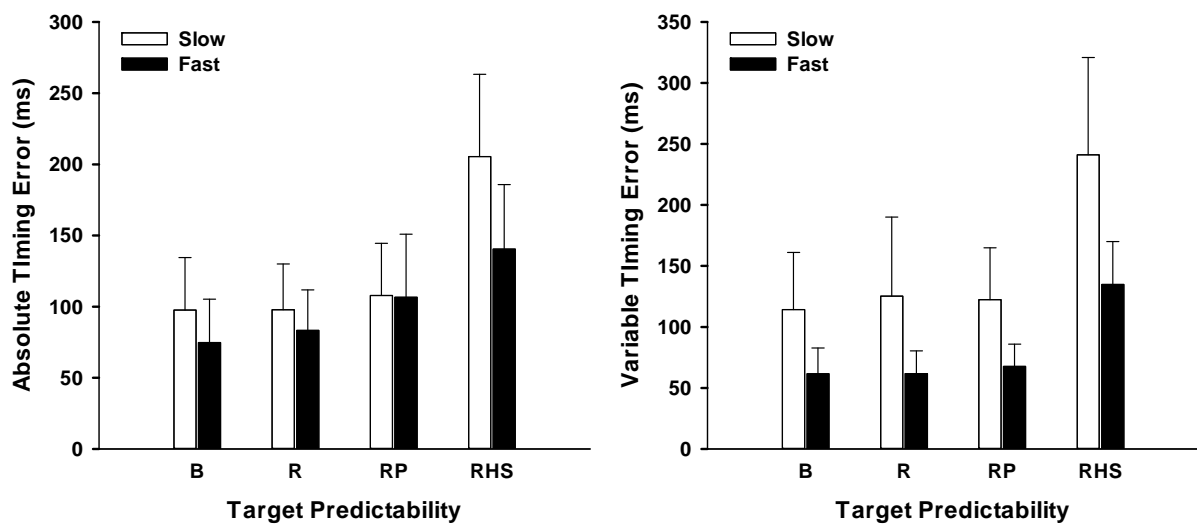
Table 4 *Summary of error scores (±standard deviation) as a function of target motion predictability and target speed*

Variable\Motion Predictability		Blocked Order Constant speed (B)		Random Order Constant Speed (R)		Random Order Random Path (RP)		Random Order Random Horizontal Speed (RHS)	
		Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast
Spatial (mm)	CE[+]	-8.0±38.2	-118.7±76.0	20.4±49.8	-137.3±86.2	14.7±54.4	-194.2±108.7	13.6±88.9	-177.6±147.6
	AE[*][+]	89.2±33.6	150.4±61.2	88.8±29.5	167.7±57.0	98.6±33.6	214.2±89.1	187.9±52.9	282.3±91.0
	VE[*][+]	104.4±42.8	124.1±42.2	113.9±59.4	124.3±37.2	112.0±38.8	136.1±36.5	220.5±73.0	271.3±70.8
Temporal (ms)	CE[+]	-8.8±41.8	-59.0±37.8	21.4±55.6	-68.3±42.8	16.2±59.5	-96.6±54.1	14.9±97.1	-88.3±73.4
	AE[*][+]	97.6±36.8	74.8±30.4	97.8±32.2	83.4±28.4	107.8±36.7	106.6±44.3	205.4±57.8	140.4±45.3
	VE[*][+]	114.2±46.8	61.7±21.0	125.3±64.8	61.8±18.5	122.4±42.4	67.7±18.1	241.1±79.8	134.9±35.2

Note. Average target speed: 915 mm/s (Slow); 2011 mm/s (Fast). $^*p < .05$ target motion predictability condition; $^+p < .05$ target speed.

Table 5 *Summary of dart landing characteristics as a function of target motion predictability and target speed*

Variable\Motion Predictability		Blocked Order Constant speed (B)		Random Order Constant Speed (R)		Random Order Random Path (RP)		Random Order Random Horizontal Speed (RHS)	
		Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast
Lab Space (Target location, mm)	Mean[*][+]	2190.1±241	2599.4±291	2202.1±248	2622.6±270	2453.1±386	2911.1±322	2182.7±416	2836.5±314
Lab Space (Dart location, mm)	Mean[*][+]	2182.0±237	2480.6±261	2212.8±247	2485.3±241	2467.9±364	2716.6±275	2196.3±392	2658.8±310
Lab Space (Horizontal, mm)	VE[*]	140.6±57.5	175.1±100.3	170.2±94.2	194.0±219.8	219.7±143.0	186.4±71.2	305.1±137.1	281.3±75.4
Lab Space (Vertical, mm)	VE[*][+]	90.1±23.5	95.9±26.2	90.4±31.9	97.4±26.2	183.6±24.6	208.6±34.1	115.4±35.5	117.8±37.7
Accurate Trials (%)	%[*][+]	43.0	25.3	45.0	22.2	19.4	8.6	20.8	11.7
Pre-test (Horizontal, mm)	VE	63.2±17.9							
Pre-test (Vertical, mm)	VE	84.6±18.1							

Note. Average target speed: 915 mm/s (Slow); 2011 mm/s (Fast). [*]$p < .05$ target motion predictability condition; [+]$p < .05$ target speed.

Table 6 *Summary of dart projection characteristics as a function of target motion predictability and target speed*

Variable\Motion Predictability		Blocked Order Constant speed (B)		Random Order Constant Speed (R)		Random Order Random Path (RP)		Random Order Random Horizontal Speed (RHS)	
		Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast
Movement Initiation Time (s)	Mean[*][+]	1.84±0.28	0.78±0.13	1.83±0.29	0.78±0.12	2.06±0.39	0.90±0.12	1.76±0.40	0.87±0.11
Movement Time (ms)	Mean[*][+]	238.2±73.6	208.3±62.9	247.0±72.5	211.6±62.9	222.4±67.2	186.1±53.7	228.3±64.3	192.8±58.9
Flight Time (ms)	Mean	312.4±60.2	299.5±61.6	314.1±63.4	310.4±66.6	327.0±78.5	317.2±62.8	305.0±71.7	304.1±68.0

Note. Average target speed: 915 mm/s (Slow); 2011 mm/s (Fast). $^{*}p < .05$ target motion predictability condition; $^{+}p < .05$ target speed.
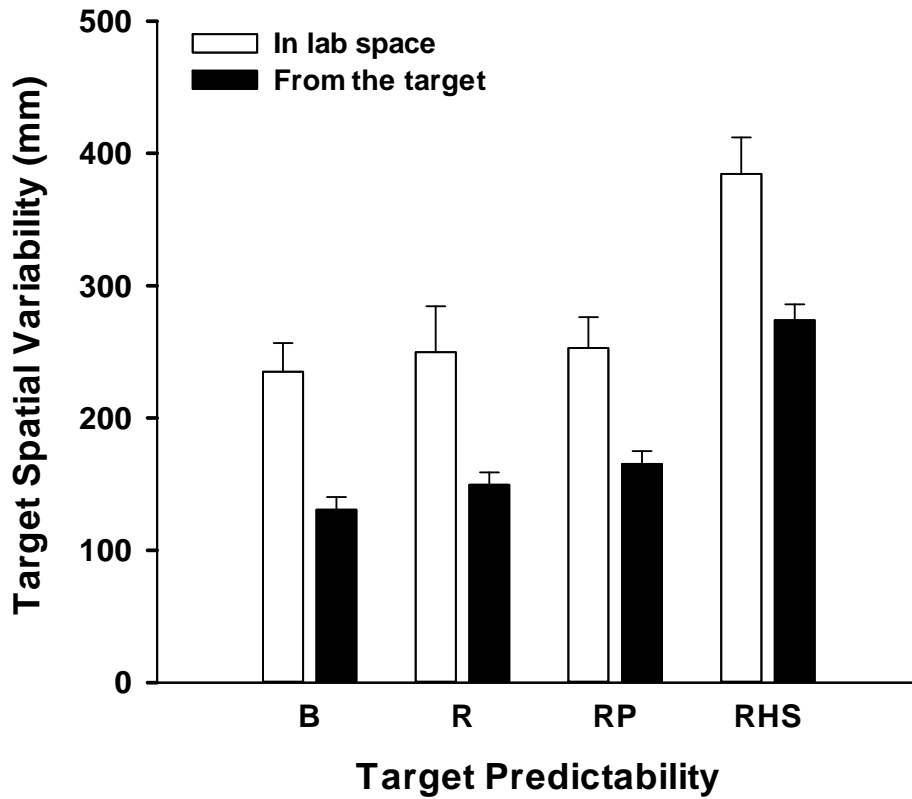
Figure 10. Interception variability in space represented with respect to the laboratory space and target (B = Blocked Order Constant Speed; R = Random Order Constant Speed; RP = Random Order Random Path; RHS = Random Order Random Horizontal Speed).

Note. Error bars represent one standard error.

Overall, faster target speeds were associated with greater constant errors and lower variability. Absolute timing errors, which are a combination of CE and VE of time, were generally lower at the faster target speed but this depended on the degree of target motion predictability.

Spatial variability of the dart landing location in laboratory space did not change significantly as target speed increased (see Table 5). However there was a significant main effect of target predictability on laboratory space variability [$F(2.11, 48.48) = 14.05, \eta_P^2 = 0.379, p <$ .01, $\varepsilon = 0.703$]. Post hoc comparisons indicated that laboratory space variability in the Random order random horizontal speed condition was significantly greater than all other conditions (*ps* <

.01). That is, a change in horizontal speed within trial increased variation in the point of aim. A pairwise comparison indicated that variability in laboratory space was significantly greater than the variability about hitting the moving target $[t(23) = 4.30, \ p < .01]$ (see Figure 10). A significant main effect of target predictability $[F(3,69) = 100.76, \eta_P^2 = 0.814, p < .01]$ and speed $[F(1,23) = 7.28, \eta_P^2 = 0.241, p < .05]$ on laboratory space variability in the vertical direction was also found. Laboratory space variability in the vertical direction was highest in the Random order random path condition. The faster target speed also resulted in greater laboratory space variability in the vertical direction. Also, spatial variability of throws during the pretest was significantly smaller than spatial variability in laboratory space across conditions $[t(23) = -9.95, \ p < .01]$.

The number of accurate trials, that is, trials where the dart landed within both horizontal and vertical target boundaries, was substantially smaller than inaccurate trials $[F(1, 23) = 284.96, \eta_P^2 = 0.925, p < .01]$ in all four conditions (see Table 5). The difference became greater with random target motion predictability profiles $[F(2.40,55.36) = 31.76, \eta_P^2 = 0.580, p < .01, \varepsilon = 0.802]$. In regards to the characteristics on the throw, the main effects of target speed $[F(1, 23) = 39.34, \eta_P^2 = 0.631, p < .01]$ and target predictability $[F(3, 69) = 3.35, \eta_P^2 = 0.127, p < .05]$ on movement time were statistically significant (see Table 6). Participants threw faster at the faster target speed (234.0 ms (slow); 199.7 ms (fast)) and in the least predictable conditions (223.3 ms (Blocked order constant speed); 229.3 ms (Random order constant speed); 204.2 ms (Random order random path); 212.0 ms (Random order random horizontal speed)). Movement initiation time was also significant for both target motion predictability $[F(3, 69) = 14.69, \eta_P^2 = 0.390, p < .01]$ and target speed $[F(1,23) = 446.99, \eta_P^2 = 0.951, p < .01]$. The dart throwing movement was initiated earlier in the fast target speed and later in the Random

order random path condition as compared to other conditions.

Eye Fixations

There were fewer fixations in the fast (2.25) than the slow (7.63) target speed [$\chi^2(1) = 282.05, p < .01$]. The number of fixation did not differ significantly among target predictability conditions. Total fixation duration [$F(1, 23) = 510.95, \eta_P^2 = 0.957, p < .01$] was also shorter when target speed was fast (average of 1.36 and 0.52 s for the slow and fast target speeds, respectively). No differences in total fixation duration were observed among target predictability conditions. The percentage of time spent in fixation did not differ among target predictability conditions but was affected by target speed [$F(1, 23) = 65.23, \eta_P^2 = 0.739, p < .01$]. Participants fixated a longer percentage of time when target speed was slow (64.5% for the slow target speed and 51.1% for fast target speed). Final fixation times did not differ between accurate (.23 s) and inaccurate (.26 s) trials. Final fixation duration (.23 s) was not longer than average fixation duration (.24 s).

POG

All twenty four participants' POG was analyzed. POG from target motion onset to dart landing was mapped onto spatial interquartile ranges described below. The coded POG data were analyzed to examine whether there were significant associations among target predictability condition, target speed, interquartile range, and POG location. The interquartile space analysis examined POG based on the position of the moving target with space normalized based on the time of each individual trial. Representative eye movement behavior in each of the target predictability conditions is depicted along with the target path in Figure 11. Note that in this figure space was not normalized to show eye movement behavior in reference to the target motion along the length of the projection screen.
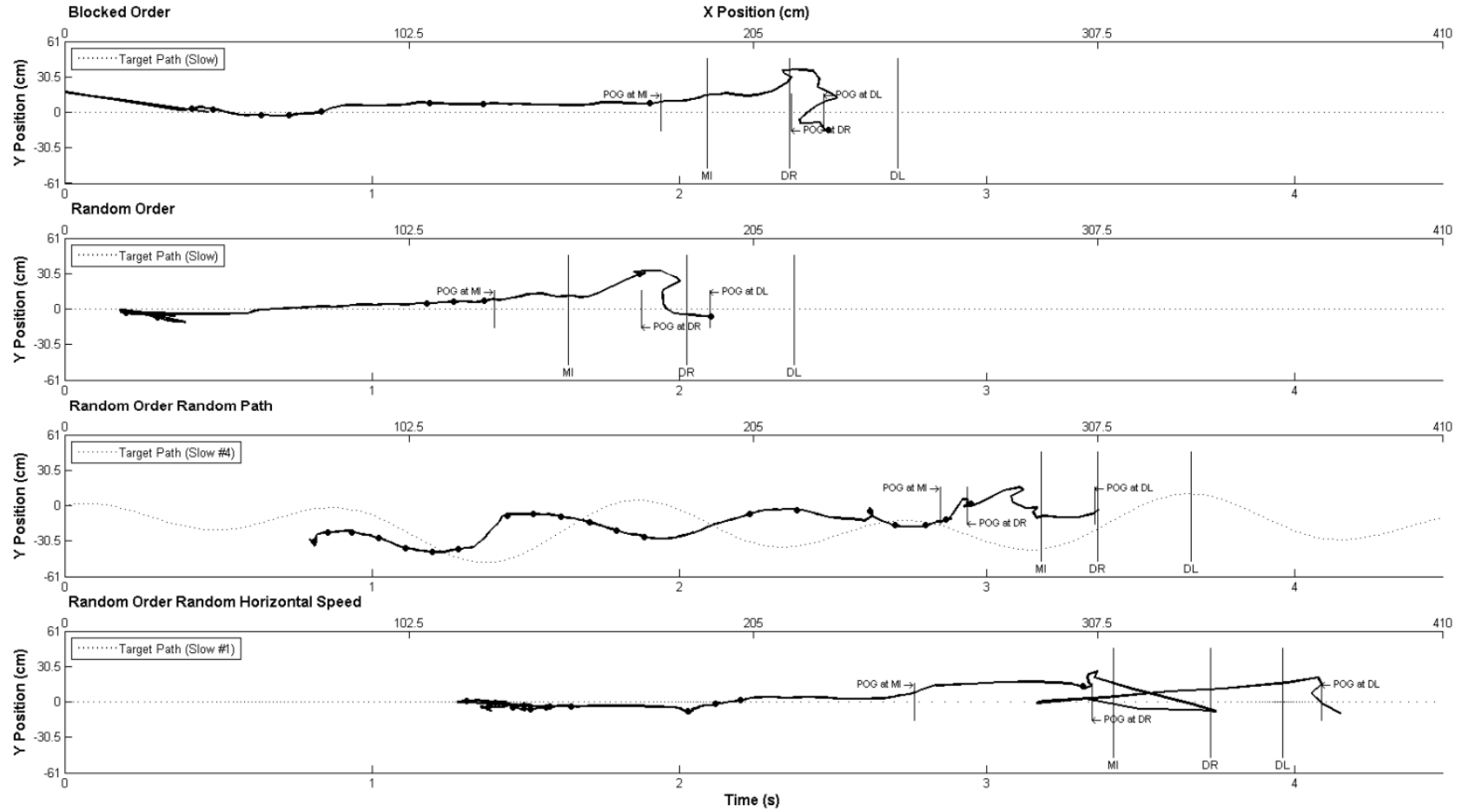
Figure 11. Representative trials for different target predictability conditions. The target path is shown with the dotted line. The dashed line and each dot depict POGs and fixations, respectively. Three critical time events, movement initiation (MI), dart release (DR), and dart landing (DL), are marked by three vertical lines with respect to the target motion (long vertical lines) and to the POG (short vertical lines), respectively.
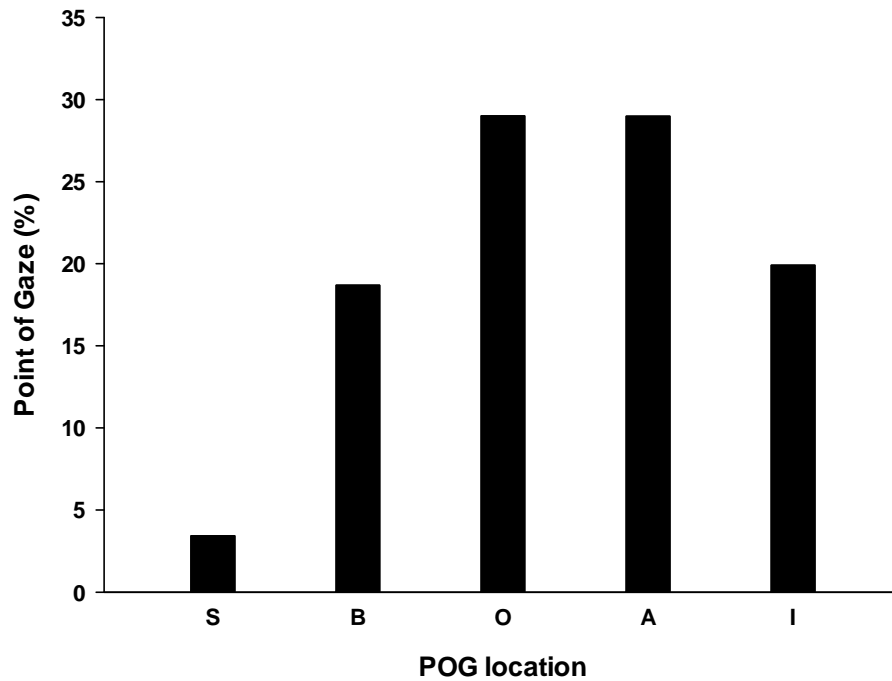
Figure 12. Main effect of POG (S = start; B = behind the target; O = on the target; A = ahead of the target; I = interception area).
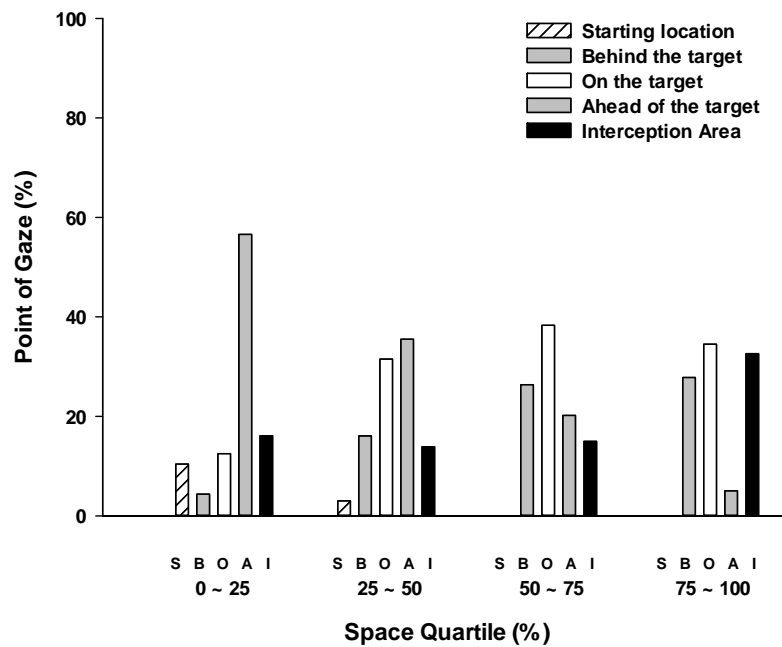

Figure 13. 2-way interaction between POG location and spatial quartile range (S = start; B = behind the target; O = on the target; A = ahead of the target; I = interception area).
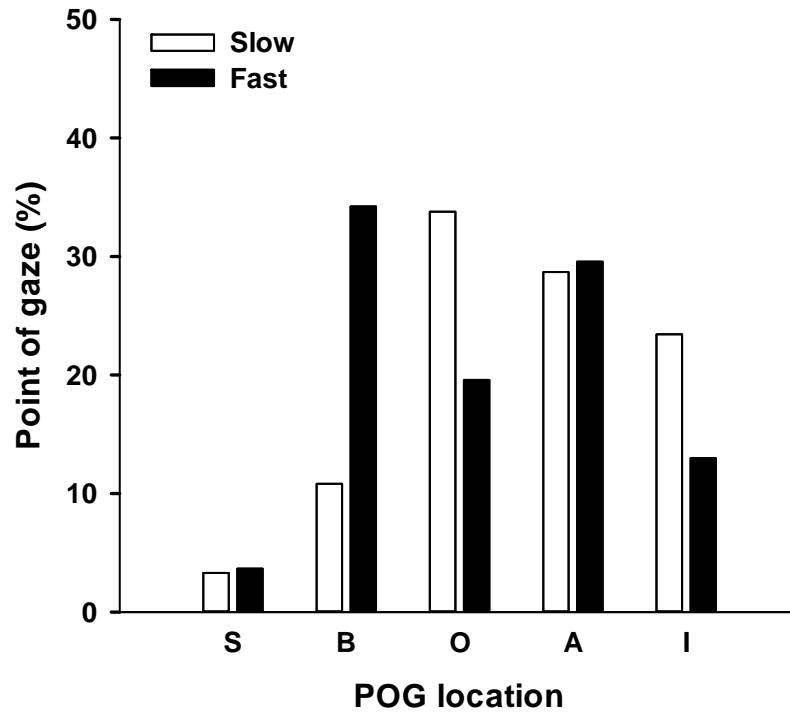
Figure 14. 2-way interaction between POG location and target speed (S = start; B = behind the target; O = on the target; A = ahead of the target; I = interception area).

POG was not equally distributed among the spatial quartiles [$\chi^2(4) = 882.45,\ p < .01$]. As can be seen in Figure 12 POG tended to be on and ahead of the target, rather than on the start location. Interception location was also frequently gazed. There were also significant interactions between POG location and spatial quartiles [$\chi^2(12) = 1096.76,\ p < .01$] and target speed [$\chi^2(4) = 330.86,\ p < .01$], respectively. As can be seen in Figure 13, gaze locations were highly influenced by the spatial location of the moving target. When the target was in the first quartile POG was largely ahead of the target. During the second and third quartile POG engaged the target more frequently and then switched to the interception point (i.e., 4th quartile). The significant target speed × POG location interaction (Figure 14) indicates that POG was on or ahead of the target at the slow speed but a significant proportion of POG was on behind or ahead the target in the fast speed. Participants looked at the interception location more

94

at the slow target speed.

There was a 2-way interaction between target motion predictability and POG location $[\chi^2(12) = 109.45, \ p < .01]$. Figure 15 indicates that when the target moved in random speed and path (RP) participants gazed less at the interception point, and then spent more time on or ahead the target as compared to other three constant horizontal path conditions. In addition, there was a significant target speed × spatial quartile range × POG location interaction $[\chi^2(12) = 32.30, \ p < .01]$. As shown in Figure 16, POG was similar between fast and slow target speeds during the first 25% of target motion. In the second and third spatial quartiles gaze tended to be on or ahead of the target at the slow target speed but behind the target at the fast target speed.
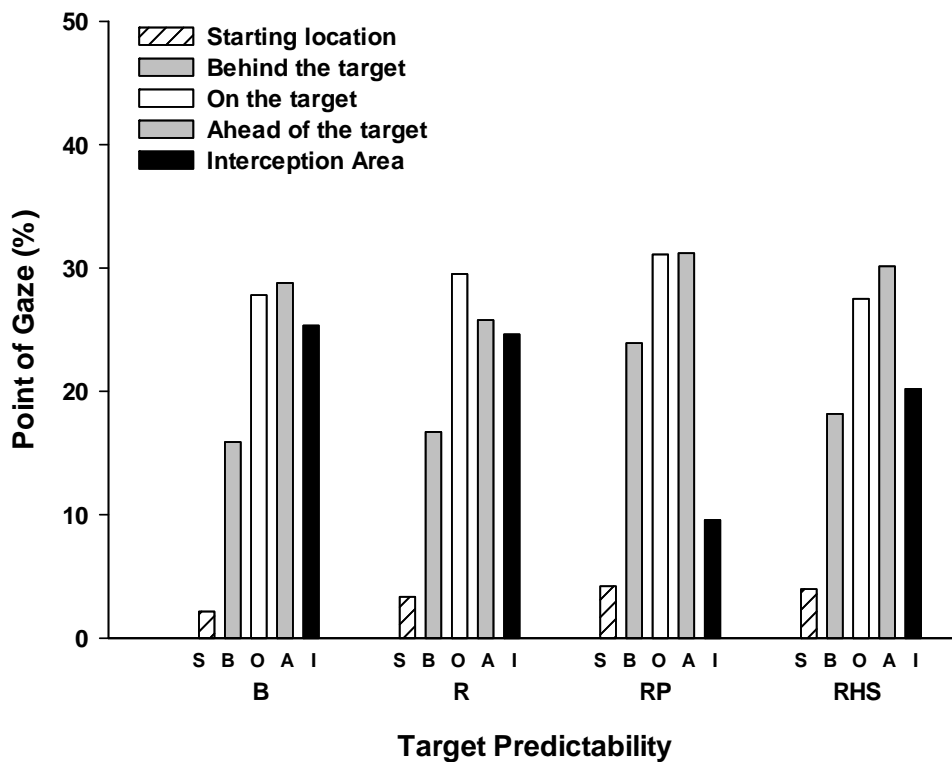

Figure 15. 2-way interaction between target predictability and POG location (B = Blocked Order; R = Random Order; RP = Random Order Random Path; RHS = Random Order Random Horizontal Speed).
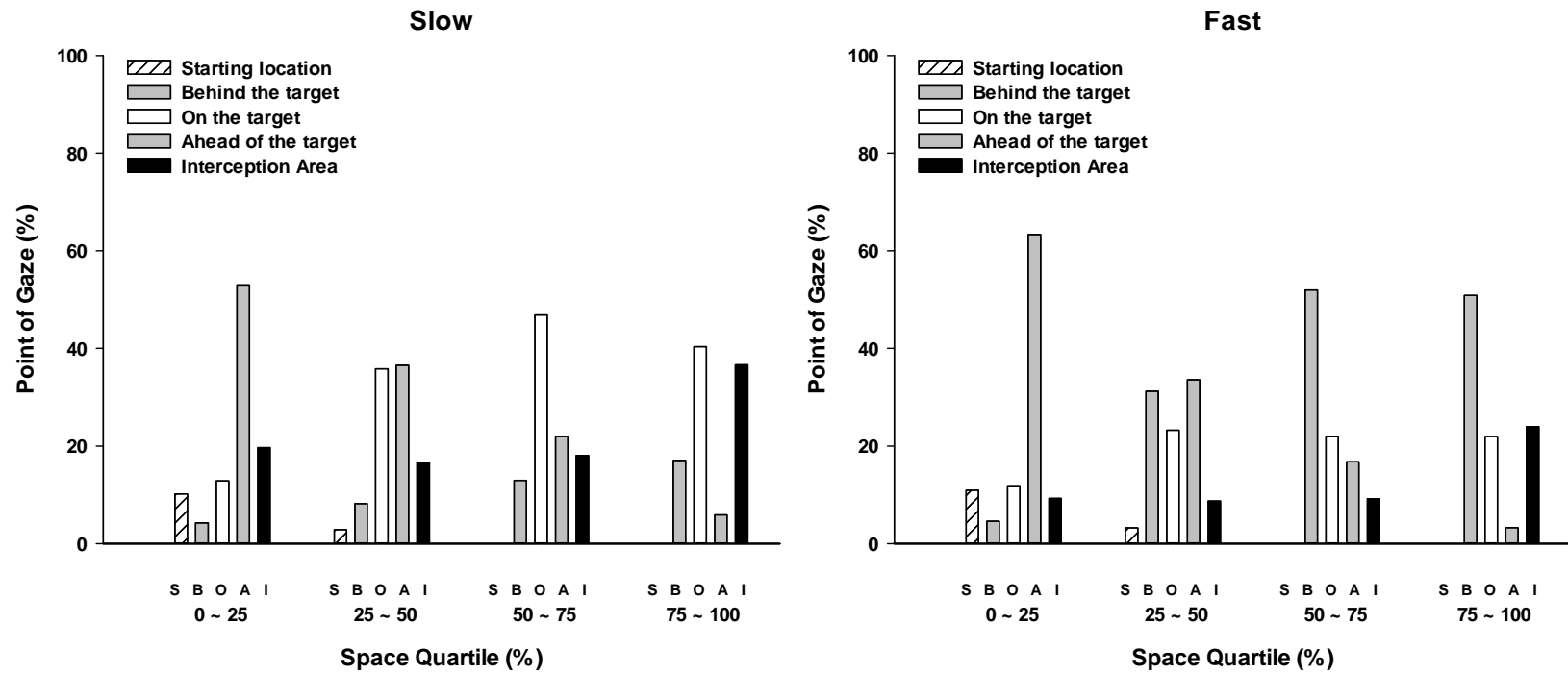
Figure 16. 3-way interaction between target speed, spatial quartile range, and POG location (S = start; B = behind the target; O = on the target; A = ahead of the target; I = interception area).

Discussion

The study was designed to understand the role of anticipation and the effect of target motion predictability in interception accuracy as well as gaze control. Experiment 2 was performed with two specific aims. The first aim was to examine whether visual search strategy and interception accuracy is influenced by the predictability of target speed in a subsequent trial. It was hypothesized that the participant would track the moving target less, and tend to foveate the anticipated interception location more, as target speed in the following trial was more predictable. It was assumed that less accurate interception performance would occur when target speed was presented in a random order. The second aim of Experiment 2 was to examine the relationship between eye movement control and target motion characteristics in interceptive aiming. It was predicted that greater randomization of spatial and temporal target motion would result in a higher degree of target information acquisition through looking at the target.

Spatial and temporal accuracy

Spatial and temporal accuracy were inversely related to each other. As the target moved faster the interception response become less accurate in space, but the timing accuracy was improved. This was the case in all target motion conditions. These results provide further evidence of a space-time accuracy relationship (e.g., Newell et al., 1994; Tresilian et al., 2009) as well as extends its robustness to conditions where target motion configurations in space and time change randomly. Target presentation order (e.g., blocked vs. random order) did not generate notable differences in spatial or temporal accuracy. The equivalent interception accuracy between blocked and random target speed presentation has also been reported in catching a projected ball (Tijtgat et al., 2010). It was expected that the blocked and random speed presentation would result in different movement planning and control strategies. Tijtgat et al. (2010) reported

97

substantial kinematic changes (e.g., movement time and peak wrist velocity profile) especially when the target speed was slow. It has been argued that movement time longer than 500 ms could be subjected to feedback adjustment of movement timing in interception (Tresilian, 2005). However, this does not seem to be the case in the present study (e.g., movement time in slow speed: 598 ms in Tijtgat et al. and 242 ms in present study). Alternatively, task constraints employed in present study, such as number of target speeds, type of movement, and selective interception location and timing, might better account for the insignificant interception accuracy differences between blocked and random order conditions.

A considerable interception bias was observed when target speed was randomized. The fast target speed led the participants to intercept the target late and the slow target speed led the participants to intercept the target early. This significant aiming bias was augmented when target motion was temporally and/or spatially randomized. That is, greater timing bias toward delayed interception was especially the case at the fast target speed for random target motion profiles. These findings demonstrate the association of target motion regularity with interception timing bias as well as replicate the findings of Experiment 1, supporting the substantial target speed effect on interception bias. The results are also consistent with findings of de Azevedo Neto and Teixeira (2009, 2011), showing the significant interception timing bias with target velocity change. Although the velocity changed in one direction, the interception timing bias effect was clear. Furthermore, random target motion change within a trial resulted in substantially greater interception error and variability as compared to constant target motion. The greater negative timing bias with a fast target speed, as well as the greater laboratory space variability, highly contributed to the increase in interception error in the random target motion conditions. So in addition to target speed, and variables constrained by target speed such as target viewing time

and/or movement time (Coker, 2006; Park, 2003; Peters, 1997), how constant the target motion profiles are in space and/or time needs to be considered for interception accuracy.

The variation in aimed location in laboratory space was significantly influenced by target motion predictability. A random presentation of target speed caused a large increase in variability in where the dart was projected. Laboratory space variability, however, was not influenced by target speed. This finding is inconsistent with a previous report that greater absolute and variable spatial error were associated with a shorter movement duration in dart throwing (Etnyre, 1998). A shorter movement time in fast target speed was exhibited in the present study. Although there was an insignificant target speed effect on aiming variability, variability in laboratory space was significantly greater than variability in hitting the moving target in all conditions. These results indicate the substantial contribution of laboratory space variability to the interception variability in hitting the moving target (Tresilian, 2009). Moreover, it may indicate that target speed alone is not enough to change the participants' tendency to aim at a pre-determined spatial location that minimizes the projection distance. A more variable context with respect to the task environment as well as to the target motion seems necessary for the participant to engage in a target dependent interception strategy. The analysis of laboratory space variability in the vertical direction confirms this notion in that much greater vertical aiming variability in laboratory space was shown when both target speed and path were randomized compared to the constant horizontal target path conditions. Participants were indeed influenced by the vertical target motion information and used that information in determining interception location in laboratory space. It has been reported that dart landing position variability between horizontal and vertical directions was similar when aiming at a stationary target (Smeets et al., 2002).

Gaze control characteristics

Gaze control characteristics were analyzed to determine how eye fixations and POG distributions are influenced by target speed and target motion characteristics. Absolute and relative fixation frequency, total fixation duration, and final fixation duration were evaluated. Gaze behavior, in general, was less influenced by target speed and target motion predictability as compared to the extent that interception accuracy was affected.

The fast target speed constrained eye movement kinematics as indicated by the reduced number of fixations and shorter total fixation durations. Relatively shorter time was spent on fixations at the fast target speed. A significant interaction between POG and target speed was exhibited. Participants regarded different spatial locations as target speed changed; looking more at the moving target at the slow target speed and the behind the target at the fast speed. This is in contrast to Croft et al. (2010), who reported no simple relationship between target speed and pursuit tracking behavior. The horizontal direction of the object's flight and the associated horizontal direction of eye movement, along with the wide range of target speed in the present study, could have contributed to these differences in findings.

It is generally assumed that gaze control characteristics are associated with accuracy in space and time. Temporally accurate interception would have been possible by looking at the interception location at the fast target speed, so that the perception of target motion was obtained based on peripheral vision. Spatially accurate interception at the slow target speed could have been achieved by maintaining the target image in the region of the fovea. Literature in which eye movement was directly controlled (e.g., fixation or pursuit tracking) has addressed the significance of eye movement control on timing accuracy rather inconsistently. The degree of visual periphery in target motion perception has been exhibited as a non-crucial component on

100

anticipation timing (Long & Vogel, 1998; Peterken et al., 1991). However, it has been also reported that time-to-contact estimation was substantially biased as target speed varied when the eyes were fixated (Bennett et al., 2010). The significant main effect of target speed on interception timing bias in the present study partially supports these findings. Further investigation, however, seems necessary to clarify whether gaze control strategy is associated with space-time accuracy as well as what makes the participant use distinctive gaze behaviors as time constraints change.

Task constraints employed in this experiment showed a significant association with POG distribution. POG was located ahead of the moving target during the initial target path but the gaze control pattern changed as the target moved in front of the participant. As the target moved in front of the participant and approached the mid-point of the projection screen, participants tended to follow the moving target frequently. The intended interception location was of interest primarily in the last quartile. The visual search pattern was very similar across conditions except the Random order random path condition. The difference was mostly due to the varied time to intercept the target. Most interceptions occurred in the third quarter of projection screen (74 %). However, when target speed and path was randomly manipulated the time to movement onset became much longer as compared to the other three conditions, indicating a longer target viewing time. For instance, participants intercepted the target in the fourth quartile for a few trials (4.5 %) when the target moved at a constant speed and path, but 21.8 % of interceptions occurred in the fourth quartile in the Random order random path condition. So, gaze control strategy was highly influenced by the participants' interception strategy, which was constrained by the speed and motion predictability of the target and also by the throwing location.

While POG allocation in a fixed global spatial frame provides useful information, it

might disregard how POG changed over time, especially, when there are significant changes in the choice of interception location and timing. POG distribution with respect to the unfolding interception movement indicated that participants attempted to foveate the moving target along the trajectory. However, the intended interception location was mostly in the participants' regard and checked more frequently in the last part of movement execution. When target speed was fast, especially, participants' POG delayed behind the moving target was switched onto the intended interception location significantly. These results are consistent with the findings exhibited during pursuit tracking with predictable object motion (Bahill & LaRitz, 1984; Vickers & Adolphe, 1997) and pursuit tracking followed by an anticipatory saccade to the critical spatial location in either unpredictable (Land & McLeod, 2000) or unable to follow target motion. Overall, the spatial and temporal analyses of POG provide a more clear picture of visual search strategy in interceptive aiming. In the present study the point of regard varied correspondingly as the target advanced in space and as the interception movement unfolded.

As in Experiment 1, the importance of final fixation duration on interception accuracy, found in previous research was not replicated. Accurate trials did not have a longer final fixation duration or a longer average fixation duration than inaccurate trials. The advantage of final fixation duration in motor skills has been well described in the context of expertise (Behan & Wilson, 2008; Savelsbergh, Williams, Van der Kamp, & Ward, 2005; Vickers et al., 2000; Williams et al., 2002). However, the task used in present study did not have a clear standard to distinguish the participants' skill level. In addition, whether or not the target was in motion, the direction of the object's motion, and the time delay associated with the collision between the effector and the projectile distinguish the present study from previous studies leading to the inconsistent finding. It should be mentioned, however, that the final fixation in experts was

initiated earlier and located on the object or near the object release point when the performer was temporally pressured by a fast approaching target (Panchuk & Vickers, 2006; Rodrigues et al., 2002). This may suggest that locating gaze on the key spatial reference, and therefore processing target motion via peripheral vision, might be important for accurate perception as well as the interception of a moving object. Pursuit tracking which minimizes the discrepancy between the moving objects location and the POG is limited and depends on the visual properties of the stimulus (e.g., direction and speed of motion) (Collewijn & Tamminga, 1984; Rottach et al., 1996).

Overall, the results support that task constraints are highly associated with accuracy as well as visual search strategy in interception. It seems more important that the performer be able to adapt their own perception and action strategy to achieve the best performance according to the constraints imposed, instead of persisting in a preset strategy. Under the constraints imposed in present study, continuous updating of target motion information with a controlled gaze while attending to the interception point might be an optimal strategy. In addition, developing constraints relevant eye-head coordination seems necessary to maintain a stabilized spatial reference in order to maximize interception accuracy.

GENERAL DISCUSSION

Interception is successful only when the effector or projected object coincides with a moving object at the right space at the right time. This inherently difficult task demands the performer produce a well-coordinated movement sequence based on accurately perceived and/or predicted object motion characteristics. Two contrasting theoretical views have dominated attempts to explain how perceived visual information is associated with the organization of timed motor responses. How perception-action process influence interception accuracy has been a main concern. Eye movement control is critical in determining the nature of perceptual information in space and time. However, the details of how gaze is controlled during interception have been often overlooked. Although previous research has manipulated a number of perceptual and response factors, one agreed conclusion is that there is no obvious link between visual search and interception performance. The accuracy of interception appears to be affected inconsistently by target motion characteristics, response organization, cognitive function, or psychological factors. Alternatively, a constraints-based interpretation was proposed to account for the emergent pattern of movement control (Newell, 1986) as well as visual search strategy (Williams et al., 2004).

This dissertation examined how constraints influence interception accuracy and visual search strategy. The role of constraints in interceptive aiming was investigated by manipulating spatial and temporal target motion configuration. The focus of the experimental studies was to not only see the changes of interception accuracy but also identify the parameter or parameters that change visual search behavior as a function of the constraints imposed. Target speed, predictability of target speed, and the path of the target were manipulated either within or between trials. Dependent measures were implemented to access accuracy with respect to the moving target, variability in laboratory space, eye fixation control, and point of gaze distribution.

104

In Experiment 1 target speed was varied in three different levels and interception location was either tightly or loosely specified. In Experiment 2, the order of target speed was randomized, target speed was varied within trial, or the target followed a randomly created motion path and speed profile. The general finding was that the manipulated constraints affected interception accuracy in a systematic manner but gaze control pattern to a lesser extent.

Control of Interception Accuracy with Constraints

The analysis of interception accuracy indicated that the most influential parameter determining interception accuracy was target speed. The interception timing response, in general, was too early for slow moving targets and delayed for fast moving targets. This was the case irrespective of whether or not the interception location was predetermined, the upcoming target speed was predictable, or the motion of the target was constant. This is consistent with studies where very high target speeds (de Azevedo Neto et al., 2011; Peters, 1997), short viewing times (Park, 2003), and/or long movement times (Coker, 2006; Peters, 1997) were employed. It has been proposed that the robust target speed effect on interception timing bias resulted from employing a spatial landmark to control the interception response (Fleury et al., 1998). Indeed, participants' movements were triggered at approximately the same target location (1720 mm in slow speed and 1690 mm in fast speed from the starting location, Experiment 2). This finding extends the notion that interception is initiated based on a fixed location in space (Fleury et al., 1998) even when no interception location was specified. However, the selection of the spatial reference to initiate throws changed with different throwing positions in the two experiments. In both experiments the spatial reference appeared to be in front of the standing position. Although a long viewing time was provided in present study, the opportunity to view the target even longer was compromised by taking the shortest throwing distance instead.

The results of the two experiments were consistent in demonstrating a systematic decrease in timing error as a function of increases in target speed. The results also showed that less accurate and more variable interception were associated with a longer duration of movement execution. This is certainly counterintuitive to the traditional accounts of the movement speed and spatial accuracy relationship (e.g., Fitts, 1954). The classic approach of the speed-accuracy trade-off, however, is incomplete and accounts only for the restricted elements of the accuracy function (e.g., Hancock & Newell, 1985). When the movement-speed timing-accuracy relationship was considered (Newell et al., 1994; Schmidt, 1969) or both spatial and temporal accuracy were required in a task (e.g., interception) (Tresilian, 2004; Tresilian & Lonergan, 2002) the shorter movement time resulted in smaller timing error and less variability. A response is more susceptible to variation as longer movement duration is permitted (Hancock & Newell, 1985). Accurate temporal estimation with increased target speed, however, has not always been the case, especially when the movement duration was very brief (e.g., key or button press). Moreover, timing accuracy has been shown to be linearly associated with movement speed (e.g., Latash & Gutman, 1992) and target speed (e.g., Tresilian et al., 2009) but not spatial accuracy. Overall, the present experiment indicates that interception accuracy interacted with a number of factors associated with target motion as well as response organization.

Another important issue regarding interception accuracy is how much variation is allowed in where the target is intercepted and how this contributes to moving target interception variability. Also, whether aiming variability is associated with constraints imposed on target motion, as well as movement constraints is of interest. As addressed earlier, in a 2-dimensional interceptive hitting task, when the movement path was loosely constrained, there was a substantial increase in aiming variability that contributed to a decrease in moving target

106

interception variability (Tresilian et al., 2009). This interdependent relationship between the range of interception location available and interception accuracy was replicated in present the experiment where the arm movement path of the participant was not restricted. Although there was no direct evidence of on-line movement corrections during the fast discrete interceptive action in the present experiments or in previous research (Tresilian, 2005; Tresilian et al., 2009), having a broader interception range along the target path seems advantageous by allowing redundant opportunities to interact with the target as compared to intercepting the target at one specific location and time.

The effects of target speed on laboratory space variability were not significant regardless of whether interception location was specified, but substantial when the target speed and/or target path profile were randomized. Constant target speed and a liner motion path led participants to rely more on a default strategy that predetermines the interception location in advance and minimizes the parameters to be controlled. Movement initiation time and movement velocity could be the participants focus while being less attentive to other parameters of the throw such as direction and speed. Consequently, the use of a conservative strategy in highly predictable conditions is associated with less variability in aiming location. Comparison between experiments, however, suggests that the availability of a wider interception location under random motion profiles did not result in superior interception accuracy. This may be because changes in target velocity or path near the time of movement initiation, and during the dart in flight, was not compensated. Also, directing throws more towards the end of display under random target motion in Experiment 2, which was a result of viewing the target for a longer period of time, required a longer throwing distance which contributed to inaccurate and more variable interceptions.

Efficient Gaze Control Strategy

The organization of point of gaze provides an indication of the most critical visual information in space and how it changes with the progress of time. Perception of visual information in time-constrained situations has typically been examined by occluding various spatial locations or time frames during the action to determine the information rich areas and the minimum time period required to extract the anticipatory visual cues. While these attempts have contributed to our understand of skill-based differences in the use of advance visual information, especially with regards to the prediction of the action intentions of opponents (e.g., Shim et al., 2005) or the anticipation of the landing location of an attacked projectile (Abernethy & Russell, 1987), studies were of insufficient ecological validity (e.g., a typical motor reaction for the sport) and were limited in determining which information is actually utilized to improve performance. As an important indicator of visual information pickup, the investigation of eye movements in the current experiments highlights the role of constraints under different task configurations. Also, the findings in present study indicate the perception and action strategy that is most appropriate for accurate interception to occur.

The experimental findings provide support for a visual search strategy that exhibits compliance with the constraints of the task. The trials of spatially bounded interception location (Experiment 1, fixed interception point) were characterized by more foveation on the reference interception point. Faster target speeds reduced the frequency of tracking the moving target and instead increased looking at the desired interception location. The target speed effect on point of gaze control, however, was influenced by parameters related to the spatial and temporal target motion characteristics (Experiment 2). Randomized target motion, especially the change of target path, led participants to have longer viewing times and look less often at the intended

interception location. Additionally, comparison between the two experiments indicates the compounded effects of randomized target speed, varying target motion profiles, and different throwing positions and how these factors resulted in more visual attention on the moving target. Gaze location was controlled to satisfy the spatial and temporal accuracy requirements by sequentially modifying gaze location to optimize both of the perception of target motion information and securing the spatial reference to throw. While point of gaze may be assumed to indicate what parts of the flight path may be important, looking at the interception point indicates that what is important may be obtained from peripheral information and point of gaze may be related to movement organization as well as obtaining information about the moving target (as with a fixed target).

Evidently, continuous tracking of the moving object was not the inherent gaze control strategy, but certain constraints facilitate a smooth pursuit of the target. This is inconsistent with findings in manual interception tasks where the natural eye movement tendency was smooth pursuit (Brenner & Smeets, 2009, 2011; Mrotek & Soechting, 2007; Soechting, Juveli, & Rao, 2009). Different experimental protocols in the current study, longer target viewing time, greater subtended visual angle due to the wide projection screen, and a longer projection distance, might provide the rationale for the different gaze control strategy in the present experiments. Independent of what the preferred gaze control strategies are, it is still not clear whether smooth pursuit is beneficial for the processing of motion information or timing judgment.

Students are instructed to 'Keep your eye on the ball' in ball sports in order to hit or catch a ball accurately. The advantage of smooth pursuit has been experimentally demonstrated with regard to the prediction of motion direction (Spering, Schutz, Braun, & Gegenfurtner, 2011) and estimation of time-to-contact (Bennett et al., 2010). However, anticipatory saccades played a

beneficial role by locating the performer's point of interest ahead of the advancing object when object motion was unpredictable (Land & McLeod, 2000) or too fast for smooth pursuit (Bahill & LaRitz, 1984; McKinney et al., 2008). Furthermore, no impairment of interceptive hitting performance with impaired foveal vision (Mann et al., 2007), or no impairment of anticipatory timing judgment (Long & Vogel, 1998; Peterken et al., 1991) without foveal vision, has been demonstrated. In line with these observations, a centrally focused fixation, termed visual pivot, is efficient in terms of minimizing saccadic suppression as well as allowing both central and peripheral eye functions specified by the retinal area (Williams & Elliott, 1999).

Smooth pursuit enhances dynamic visual acuity by keeping the object on the retina and contributes to motion perception with the aid of extra-retinal input (e.g., efference copy). However, pursuit tracking is relatively slow (e.g., up to about 100 °/sec, Spering & Gegenfurtner, 2008) and is subject to misperception of object motion due to background motion. On the other hand, when the eye is fixated there is retinal slip, a mismatch between POG and target location, and there is a high correlation between gaze change and the location of the aiming point (Henriques, 2002) such as in driving on a winding road (Marple-Horvat et al., 2005). Consequently, neither gaze control strategy is free from error. Thus, the employed visual search strategy needs to be understood in the context of maximizing performance accuracy and consistency under given constraints. The current findings support that whether or not eye follows a moving object is highly task dependent.

The importance of the final gaze fixation duration before movement initiation, that has appeared in goal-directed aiming and interception tasks, was not replicated in the present study. The final fixation has been emphasized as a medium linking eye movements and attention for the purpose of performance optimization. A longer duration final gaze fixation has been associated

with skill level, task complexity, and accuracy. It should be noted, however, that the considerable evidence linking longer final fixations and performance is limited to targeting and interceptive timing tasks, where the goal object is fixed in space or moves toward the performer. In the one study examining visual strategy where the object moves across the visual field (Causer et al., 2010, skeet shooting), skill level and accuracy were a function of a longer duration of tracking gaze. This might highlight not only the constraints imposed on the task (e.g., speed of the effector and effector-eye coordination) but also the ability to control the gun. A stable tracking gaze on the moving object, however, may or may not be associated with eye motion. The control of tracking gaze could be accomplished by head or even whole body rotation, and eye rotation may play little role. It has been demonstrated that aligning the head and/or eye position to the direction or location of aiming increased the accuracy of pointing (Henriques, 2002; Rossetti et al., 1994) and improves interceptive hitting (Lafont, 2008). Given a variety of constraints, such as in the current study, it might be more important to keep a stable spatial reference for aiming by exploiting the coordinated structure of the eye, head, and trunk, rather than continuously foveating the moving target.

Implications for Visuo-motor Coordination in Interception

The quality of interceptive aiming is determined not only by the tight coordination between perception and action but also by adaptability to the imposed constraints. Features associated with a target (e.g., size, color, and motion) exist at any given location and time requiring several control parameters to be specified in the process of transmitting visual information, initially obtained in retinal coordinates, to the motor system acting onto the global coordinate frame (Zago et al., 2009). Clearly, the variables involved in these procedures influence the outcome of visuo-motor coordination in interception. For instance, functionally

distinguished dorsal and ventral visuo-motor pathways are associated with different retinal areas and require unique eye-head control in order to obtain an appropriate source of target motion information required for the task. Eye movement control may operate for the purpose of obtaining the cues used to time an interception (dorsal) as well as the cues used to place the interception in space (ventral) as a function of the intrinsically separated visual system. However, neither the anatomical and physiological properties of the visual system, nor the priorities between the spatial and temporal cues to be employed, are predetermined. Moreover, what and how information is picked up is also dependent on the one's ability to establish advanced perceptual processes (e.g., expertise, task-related knowledge, or anticipation). Therefore, the emergent property of the whole body action (Newell, 1986) and visual search strategy (Williams et al., 2004) will be determined by the interaction between constraints imposed on the organism, the task, and the environment.

Summary

In summary, the dissertation showed the following key results:

(1) The interdependent spatial and temporal accuracy relationship associated with target speed was robust and independent of task constraints. Specifying interception location increased interception timing error. Acceleration or deceleration of the horizontal speed resulted in the greatest interception error. Interception location variability in laboratory space was not influenced by the target speed. However, spatial variability of the thrown dart in laboratory space was greater as target speed and path become less predictable.

(2) The eye did not follow the moving target all the time even at slow target speeds. The spatial location where the dart will coincide with the moving target was the predominant point of interest. Constraining interception location induced frequent gaze orientation to

112

the fixed interception point. Making target motion less predictable increased gaze on the moving target, nevertheless, the anticipated interception location was still a focus. Final fixation duration did not differ from other fixations and was not associated with interception accuracy.

(3) A task specific interception strategy is required. Although the physiological structure of the visual system plays an important role in locating gaze in space, gaze reorientation as the target moves may not be exhibited unless the task constraints require this for optimal performance. This highlights the importance of considering the task context along with the functional role of the eye. The eye, head, and effector maybe coordinated to both optimize perceptional resources as well as facilitate accurate object interception.

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133

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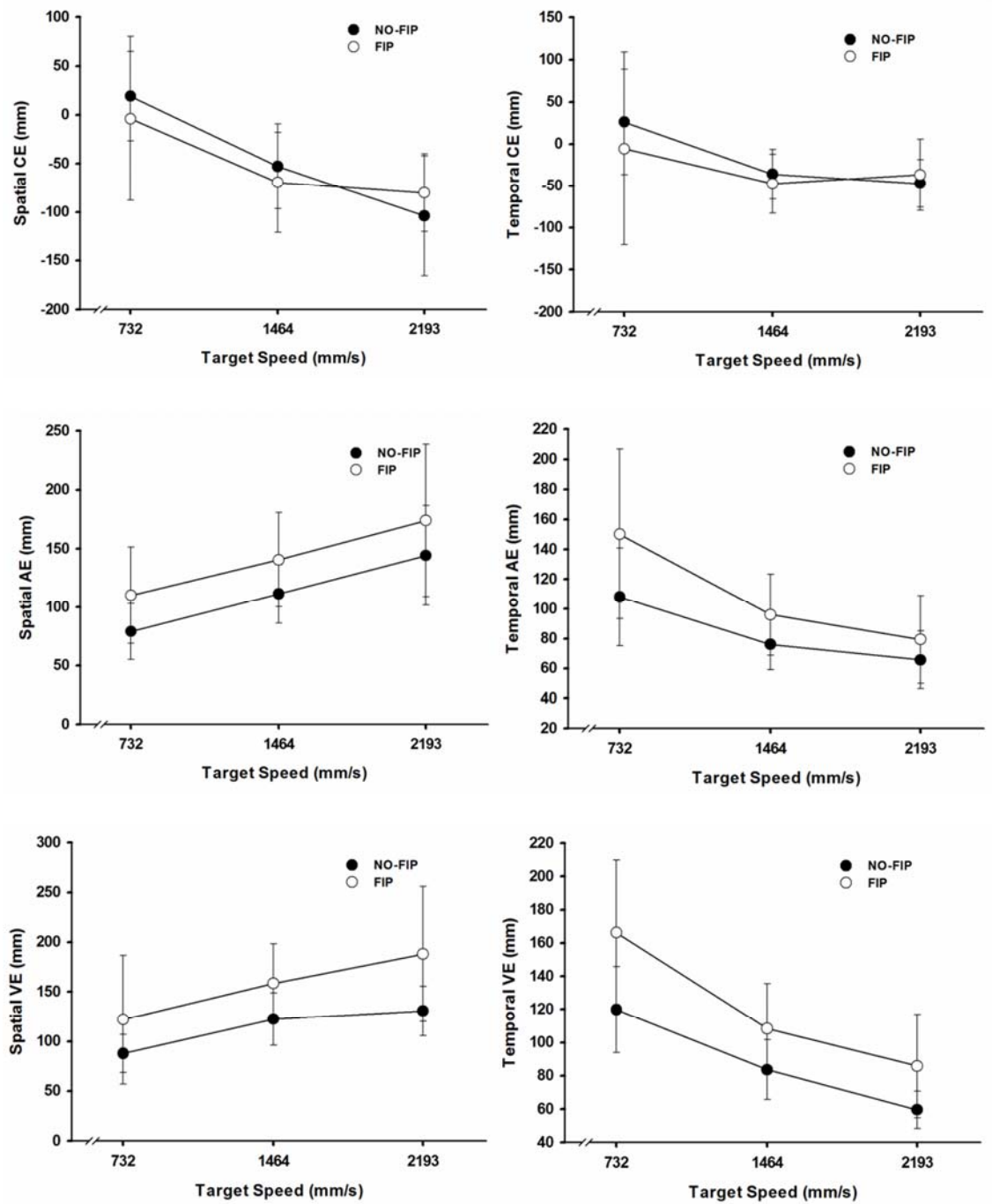
Throw and eye movement characteristics as a function of target speed and point of interception

Variable\Speed	Slow (792 mm/s)		Medium (1464 mm/s)		Fast (2193 mm/s)	
	NO-FIP	FIP	NO-FIP	FIP	NO-FIP	FIP
Flight time (ms)*	332.6±55.4	317.7±64.6	322.9±63.1	312.0±56.7	296.1±47.4	296.1±69.4
Number of fixations*	11.5±4.8	10.6±3.8	3.7±1.8	4.4±1.1	1.9±0.9	2.5±0.5
Total fixation duration (s)*+	3.40±0.63	3.01±0.51	1.36±0.57	1.49±0.34	0.85±0.38	0.94±0.25
Relative fixation time (%)+	72.9±13.9	72.1±11.8	62.1±26.6	75.1±16.8	61.0±27.4	75.1±18.7

Note. NO-FIP = no Fixed Interception Point. FIP = Fixed Interception Point.

$^{*}p < .05$ target speed; $^{+}p < .05$ target speed x interception point