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Visuo-Motor Coordination in Table Tennis

by

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Abstract

The purpose of this study was to determine how the acquisition of visual information through movements of the eyes and head affected the execution and accuracy of a complex motor skill. Participants performed a table tennis forehand stroke to right or left target area under Pre, Early, and Late-cue conditions. The visual cue was presented respectively a mean of 2,366, 521, and 327 ms before participants to contact the ball. Quiet eye (QE, Vickers, 1996a), tracking during movement time (TMT), and eye-head stabilization (EHS, Ripoll & Fleurance, 1988) characterized gaze behaviour. Movement time (MT) and velocity of arm at ball-bat contact (AVC) assessed arm behaviour. The three-dimensional kinematics of simultaneous line of gaze, head, arm, and ball motion was quantitatively described in a natural environment for the first time. In the Pre and Early-cue conditions, both high and low skill participants tracked the ball in the initial part of ball flight (QE) and kept the gaze stable on a location in advance of the ball prior to ball contact (EHS). The ball was not tracked late in ball flight, with TMT being observed in only 16 of 480 trials. The effect of skill level was observed through an early onset of ball tracking, which led to higher levels of accuracy only for the high skill group. The manipulation of cueing showed the limits of adaptation to maintain accuracy on the target. Participants were able to accommodate Early-cue levels of constraint by using a shorter QE duration, earlier QE offset, and reduced AVC. In the Late-cue condition, a generalized decrease of gaze, head, and arm movement was not sufficient to preserve accuracy. QE onset and offset occurred earlier and QE duration declined. AVC remained reduced compared to the Pre-cue condition. Horizontal movement of gaze and head declined as well. EHS onset, duration, and offset did not differ significantly across cue

conditions. There were no significant changes in MT duration across cue conditions. The occurrence of both QE and EHS within a trial decreased from 83%, to 79%, to 38% of trials during the Pre, Early, and Late-cue conditions, respectively.

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Introduction

Complex sport situations, such as hitting a moving ball towards a target, or even easily performed everyday activities, such as reaching for a cup of coffee, require a great degree of mastery in combining different sources of sensorial information and regulating the output of the action adequately. The question of how the acquisition of visual information through movements of the eyes and head contributes to the execution of motor skills in natural environments has motivated the present study.

Imagine how someone playing table tennis controls his or her eyes, head, and arm movements. A variety of aspects must be defined in terms of obtaining visual information adequate to position the bat (paddle) in the right place at the right time. Is it necessary to look at the ball before starting the arm action? How long does the ball have to be tracked or fixated and during which parts of the arm motion? Does the head move and to what extent? How does the position of the ball relative to the body influence the action? How are the changing spatial characteristics of the ball visually coded? How fast does the arm move? How fast can the planned action be stopped or changed or otherwise modulated? How does the previous experience in the task affect performance? Investigating such questions can contribute to our understanding on the relations between perception and action (Bernstein, 1967, Bootsma & van Wieringen, 1990; Gibson, 1979/1986, Milner & Goodale, 1995; Ripoll, 1991; Vickers, 1996a).

The present study focuses on how humans are able to coordinate demands from vision, head and arm control in performing a complex motor skill. In the following section, the notion of visuo-motor coordination is reviewed, followed by attentional requirements involved in action. The structure and function of the eyes and visual behaviours are described. Studies involving gaze, head, and arm movements are then reviewed, followed by the notion of quiet eye (Vickers, 1996a). Finally, table tennis studies are focused and the mechanism of eye-head stabilization (Ripoll & Fleurance, 1988) is presented.

Review of Literature

What is Visuo-Motor Coordination?

The process of governing the interactions among distinct components in a motor skill is typically investigated under the notion of coordination. One of the first to study motor coordination was the Russian physiologist Nicholai A. Bernstein. Bernstein (1967) defined coordination as "the process of mastering redundant degrees of freedom of the moving organ, in other words its conversion to a controllable system. More briefly, co-ordination is the organization of the control of the motor apparatus" (Bernstein, 1967, p. 127).

Bernstein pursued the problem of how many degrees of freedom of the body can be regulated in the course of activity by an executive having minimal intelligence and with minimal intervention in the process (Kugler, Kelso & Turvey, 1980). Bernstein's view of coordination has been interpreted in mathematical terms as the function that constrains the potentially free variables into a behavioural unit. The notion of control is defined as the process by which values are assigned to the variables in the function (Newell,1985; Kugler, Kelso & Turvey, 1980). Thus, coordination and control can be independent in the performance of an action and the task overall goal could be achieved by changing coordination, control, or both (Sparrow, 1992). Skill, in this context, is associated with the assignment of optimal values to the controlled variables (Newell, 1985, 1986; Newell & McDonald, 1992). In other words, skill is defined as the ability to correctly coordinate and control movement to achieve a task goal (Sparrow, 1992).

The theoretical conceptualization of motor coordination originated by Bernstein refers primarily to the execution of a movement where the many possibilities allowed by human anatomical and physiological structures have to result in one specific action. This focus on the organization of the output response has generated a considerable amount of research on intra-limb (relation between movements of limbs segments of the same limb) and inter-limb coordination (relation between the movements of two or more different limbs, or segments of different limbs). However, when the research aim is to understand the organization of both the motor and sensory components of an action, additional perceptual aspects have to be considered. The coordination problem involves the processing of sensory information from many sources (input) to result in movements of multiple-effectors (output) (Haggard, 1992).

Kelso (1996), summarizing Berstein's work, defined coordination in terms of six themes. First, movements are goal directed; they are done for some purpose that can be identified. Second, in order for a movement to be produced successfully the organism has to gain control over the large number of degrees of freedom and convert them into a controllable system. The difficulties associated with defining the parameters of a coordinated system are known as "the degrees of freedom problem", or " the difficulty in explaining the simultaneous control of multiple independently moving body parts" (Schmidt & Lee, 1999). Third, the solution to the degrees of freedom problem lies in the presence of synergies that intercorrelate multiple joints in space and time. To date, the detection and confirmation of this process has eluded researchers. Fourth, all movements possess a structure (or topology) and a metric (Kelso, 1996). These aspects of coordination are viewed as being quite independent of one another as when a person's handwriting remains the same regardless of whether it is large or small (Viviani & Terzuolo, 1983). Clearly, a coordinated system has a central pattern for movement that is stored in some way independent of the individual muscle units and effectors that carry out the action. Fifth, there must be some sort of brain trace that corresponds to the temporal structure of the whole action. Such hypothesized engrams were conceived to be abstract, high level, and not related to the muscle structure per se. Sixth, and finally, coordination was defined as based on a specific organization among components or elements (Kelso, 1996). This view suggests that some elements within the system are more important than others in determining optimal function although the isolation and detection of these elements has yet to occur (Latash, 1996; Schmidt & Lee, 1999).

Gregory (1987) described coordination as first and foremost a spatial problem, one in which visual information must contribute to a solution.

> "Almost everything that a human does involves the perception of the spatial locations of objects ... the spatial location of an object is compounded by the fact that sense organs are attached to mobile parts of the body. For instance, the receptive surface of the eye (the retina) is attached to a mobile eyeball, which in turn is attached to a mobile head. If we wish to know the direction of a seen object with respect to the torso, the position of the eyes and of the head must be taken into account, along with information about the retinal position of the image of the object." (p. 727).

In addition to determining how the system locates and fixates or tracks an object in space, a coordinated system is one that is functional, it is able to reach out, grasp and manipulate objects of various kinds or direct them to targets. Grasping or striking objects in a temporal, sequential fashion are all functions of a coordinated system. Finally, a coordinated system is one that results in accurate performance. An object is grasped and moved to the correct location or intercepted and propelled accurately to a target. In contrast, an uncoordinated system is one that exhibits imprecision, errors and inaccuracy in performance. An additional aspect of visuo-motor coordination is its relation to attentional demands, which is shown as follows.

Attention and Selection-for-Action

Specification of a unique set of time-varying parameters is a requirement for the execution of any goal directed action, a set of these parameters that determines a particular action from among numerous possibilities (Allport, 1989). Consider, for example, a person reaching to catch a moving object. Many different objects may be present in the visual field, but information specific to just one of these objects must uniquely determine the spatio-temporal coordinates of the final position of the reach, the orientation and aperture of the hand, and so on. The broader array of information available about the positions and sizes of other objects within view must not be allowed to interfere with these parameters, although they may influence the trajectory of the reach in other ways. Consequently some selective process is necessary to map just those aspects of the visual array, specific to the target object, selectively onto appropriate control parameters of the action. This functional requirement Allport (1989) termed "selection-for-action".

Allport (1989) emphasized that selection-for-action does not necessarily imply binary division of information between "selected" and "unselected". Often, distinct concurrently available sources of information (potential control parameters), sometimes in different spatial locations, have to be selected for control of different parameters of action at the same time. An important requirement for success of such coordination in quasi-independent, concurrent tasks is to keep the streams of information appropriately segregated to avoid unwanted crosstalk between them. Performance of many concurrent task combinations can be limited by the ability to segment and to keep separate different processing streams. Visual information that is selected to control a particular set of action parameters may be sharply localized, as an approaching ball among several, or may be comparatively global, such as an optic flow field. For effective visuo-motor control, visual selection-for-action must be capable of being focused selectively on a coherent source of visual information, however that information might be distributed spatially in the visual array (Allport, 1989).

Neumann (1990) identified two types of selection problems in action control, namely effector recruitment and parameter specification. The effector recruitment problem refers to the fact that effectors must be recruited in such a way that no mutually incompatible actions are attempted. To overcome this problem the system needs mechanisms of behavioural inhibition that can "gate" between competing action tendencies. The parameter specification problem occurs when an intended action can be executed in many different ways, only one of which must be selected at any instant (Williams, Davids & Williams, 1999). The following sections change the emphasis from visuo-motor coordination and attentional demands to the anatomical and physiological characteristics of the eyes and visual behaviours.

Structure and Function of the Eyes

Eye movements are used to direct information onto the fovea, the 1-2 degree central cone-rich area of the retina that provides the highest acuity or clarity and best colour vision. The fovea is composed largely of cone receptors in its very centre, the fovea centralis. Because of the one-to-one relation between central cones, bipolar and ganglion cells found in the next nuclear layer in the retina, the fovea supports fine visual discrimination. Acuity decreases quite rapidly as the stimulus moves from the fovea into the peripheral retina. The decrease in visual clarity is due to the reduction in cone density, and increase in rod receptors towards the periphery. Because of their many-to-one mapping with the underlying ganglion cells, rods are not able to provide detail and colour but are sensitive to light and motion (Bruce & Green, 1990; Coren, Ward & Enns, 1994; Kandel, Schwartz & Jessell, 1991). Cones transduce electromagnetic energy over a limited range of wavelengths (i.e., visible spectrum) into graded potentials, which are then transmitted by the bipolar and ganglion cells to the brain as action potentials for interpretation (Kandel, Schwartz & Jessel, 1991).

In performing tasks involving rapid change, such as many sports, performers must continuously adjust eye position to maintain optimal visual clarity (Williams, Davids & Williams, 1999). The necessity of keeping the retinal image as stable as possible results in a characteristic pattern of eye movements in humans and many other species. This pattern consists of periods of stationary fixation, which can be changed by fast gaze-relocating eye movements called "saccades", or by slower movements called smooth pursuit or tracking (Land, 1995).

Visual Behaviours Investigated in this Study

When the eyes view a small object, like a table tennis ball, two general types of eye movements can be observed: fixations and smooth pursuit eye tracking. Fixations are durations in which the eyes remain stable on some aspect of the environment, enabling the performer to stabilize an informative area of the field of view in foveal vision, in turn, allowing more detailed processing to occur. Researchers have assumed that fixation duration is an indication of the relative importance and complexity of the fixated area or object. The underlying assumption is that the more visual information has to be processed, the longer fixation duration (Carpenter, 1988; Just & Carpenter, 1976). Consequently, fixation duration can vary considerably depending on the nature, difficulty, and time constraints of the task and the visual scene that are available to the observer. In laboratory investigations, minimum gaze duration of a fixation has varied from 80 to 150 ms, with the lower durations found in situations where participants perform highly practiced skills (Optican, 1985; Carl & Gellman, 1987). In sport situations, relatively high fixation durations have been reported in complex scenes, such as 850-1500 ms in soccer (Williams & Davids, 1998) and 320-380 ms in squash (Abernethy, 1990). On the other hand, values as low as 100 ms can be found for highly practised performers or for viewing of familiar stimuli, such as can occur in golf putting (Vickers, 1992).

The visual search literature suggests that fixation location and duration characteristics are indicative of the perceptual strategy used by the performer (Williams & Davids, 1998). Fixation location is assumed to indicate the importance of cues used in decision-making; the number and duration of fixations are presumed to reflect the information processing demands placed on the performer (e.g., Abernethy, 1985; Goulet, Bard & Fleury, 1989). These assumptions have been subjected to a number of challenges (Vickers, 1996b; Williams, Davids & Williams, 1999). First, visual orientation may not be directly related to attention. Subjects are able to relocate attention within the visual field without making distinctive eye movements to changes in the point of fixation (Posner, 1980; Williams & Davids, 1997, 1998). There are numerous situations in sport, where a performer's gaze may be directed to one location while attention is allocated elsewhere (Williams & Davids, 1998). It may be possible to fixate an object without extracting specific information, which implies that "looking" (fixation on the fovea) and "seeing" (information processing or cue extraction) are different processes (Abernethy, 1988; Vickers, 1996b; 1996c).

Smooth pursuit tracking eye movements are relatively slow, continuous movements of the eyes to follow a moving target; if target speed is not too high, eye movement velocity is matched to target velocity (Carpenter, 1988). It has been established that: a) pursuit movements can occur in any meridian but are smoother and more precise in the horizontal direction (Rottach et al., 1996); b) maximal tracking velocities achieved in humans range between 80 deg/s and 160 deg/s depending on the type of target (Meyer, Lasker & Robinson, 1985); c) retinal velocity of image motion and position errors greatly enable the maintenance of smooth pursuit eye velocity (Seagraves & Goldberg, 1994); d) there is no perceived change in target velocity as long as the relative motion between target and background is maintained (Brenner & van den Berg, 1994); e) randomization of target step amplitude or onset reduces the frequency of anticipatory smooth eye movements but does not completely abolish them (Moschner, Zangemeister & Demer, 1996); and f) smooth-pursuit of self-moved target presents a shorter delay and a higher maximal velocity than in eye-alone tracking (Vercher, Quaccia & Gauthier, 1995).

Rapid changes in the visual array make it difficult to follow an object visually using pursuit tracking eye movements (Haywood, 1984). At excessive speeds, it has been shown that expert sport performers do not track a ball during its entire flight path (e.g., Bahill & LaRitz, 1984; Hubbard & Seng, 1954; Ripoll, 1991; Ripoll & Fleurance, 1988; Vickers & Adolphe, 1997). These studies demonstrate the inability of the performer to maintain visual tracking during rapid ball flight, which directly contradicts advice often given by sports coaches to "keep your eye on the ball" (Williams, Davids & Williams, 1999). This type of recommendation may be more related to maintaining a stable head and body position during skill execution than the possibility of extracting operational information from the ball's flight.

Other Visual Behaviours

As noted, saccades are fast movements of the eyes used to bring a new part of the visual field to stable fixation of the foveal region of the retina (Carpenter, 1988). The requirement of image stability is a consequence of anatomical and physiological features of the visual system. The field of view of humans, like that of most predators, is relatively limited. Thus, eye movements allow inspection of a much larger portion of the visual field than is available in a single fixation (Carpenter, 1988; Kandel, Schwartz & Jessel, 1991). While reduced, there is sensitivity during saccades (Volkman, Schick & Riggs, 1968).

To ensure clear vision during head movements, gaze is stabilized by the vestibulo-ocular reflex (VOR). The specific function of VOR is to match the velocity of the eye to that of the head, in an attempt to keep the image of the outside world stationary on the retina (Carpenter, 1988). The VOR depends on information from the inner ear that registers motion of the head within each movement plane (Rosenbaum, 1991). Compensatory eye movements produced by VOR are much more rapid (about 16 ms) than movements attributed to the visual system alone (about 70 ms) (Lee & Zeigh, 1991). Despite the apparent importance of VOR in motor skills, relatively few studies have investigated the interaction between eye, head, and body movements. A primary reason for this may be technical difficulties with eye movement registration systems, which are of restricted utility in dynamic task situations. As a consequence many studies have required subjects to hold their head as still as possible during testing (Williams, Davids & Williams, 1999). This seriously limits the generalizability of their findings to "real-world" dynamic tasks.

Line of Gaze and Eye-Head Coordination

The line of gaze is defined as the imaginary line in space from the target through the centre of pupil to the fovea (Daniel & Lee, 1990). To obtain detailed information about a feature of the environment, line-of-gaze must be held stable on that feature. Gaze stabilization when the body and/or object is moving, as in table tennis, usually requires tracking the object with the line-of-gaze within the field of view (eye tracking) and also with the field of view itself (head tracking) (Daniel & Lee, 1990). One explanation for the coordination between eye and head tracking is based on the idea that programming of saccades is identical, irrespective of whether the head moves or not. If the head does move, the vestibularly induced eye movement is added linearly to the saccade signal (Guitton, 1988). In this case, saccade velocity and amplitude decreased according to velocity and amplitude of head movement (Bizzi, 1974). This hypothesis has been called the addition hypothesis (Robinson & Zee, 1981) or linear summation hypothesis (Laurutis & Robinson, 1986) and expressed as an oculocentric view of eye-head coordination (Guitton, 1988).

The linear summation hypothesis has some limitations mainly due to situations in which the target is beyond the oculo-motor range. It seems to be valid only for gaze shifts smaller than 10 deg and a "transition point" for larger gaze shifts is highly variable (Guitton, 1988). An alternative explanation has been developed more recently called the "gaze feedback" hypothesis (Guitton, 1988; Guitton & Volle, 1987; Schmid & Zambarbieri, 1991). It is based on the internal reconstruction of the desired and current gaze position and the comparison between these. In this view, the accuracy of the final gaze orientation is guaranteed by a gaze feedback loop which controls the saccadic mechanism. According to this hypothesis, the vestibular system is used only to generate the compensatory eye movements.

One interesting finding by Guitton and Volle (1987) is that saccadic amplitude was a function of head velocity in situations in which head motion was not perturbed. For a given target offset, the faster the head motion the smaller the saccade. Also, it has been demonstrated that saccadic eye movements and head movements may be initiated at quite different times relative to each other, depending on factors such as target amplitude, predictability and visibility (Barnes, 1979; Bizzi, Kalil & Morasso, 1972; Funk & Anderson, 1977; Guitton & Volle, 1987; Zangmeister & Stark, 1982). For example, it has been shown that predictability can influence the initiation pattern of eye and head movements. When monkeys were required to move their eyes to an unexpected appearing target, the initiation of eye movements preceded that of the head. An interaction between eye lead time and target eccentricity occurred such that the amount that eyes led the head decreased as target eccentricity increased (Guitton & Volle, 1987); conversely, when monkeys fixated on a predictable target, head movements began before a saccade was generated (Bizzi, 1974; Bizzi, Kalil & Morasso, 1972). The literature reviewed above has general applicability to the process of eye-head coordination in motor skill situations. It seems, however, that eye-head coordination in table tennis is additionally influenced by the movements of arm. The consideration of arm movement in eye-head coordination is discussed in the following section.

Eye-Head-Arm Coordination

Carnahan (1992) described a technical or methodological difficulty in comparing the movement of the eyes, head, and arm. She stated that it is very difficult to find a common metric of comparison so that coordination can easily be described and quantified. A possible solution would be to compare eye and head rotations with limb translations by using temporal information about landmark events in the eye, head, and arm kinematics profiles (Carnahan, 1992; Carnahan & Marteniuk, 1991, 1994). Another would be to quantify limb movements in terms of rotation and compare these directly to eye and head movements (Hore, Goodale & Villas, 1990). The approach used in the current study was similar to the latter one. The description of gaze and arm movements in table tennis was based on three-dimensional rotations of line-of-gaze and arm in space.

Biguer, Jeannerod and Prablanc (1982) were among the first to examine eye, head, and hand coordination in humans. They used the task of directing eye, head, and arm movements to the same visual target. Their results showed that the eyes started to move first, followed by the head and the finger towards the visual target. Electromyographic (EMG) recordings of the muscles, however, indicated essentially a simultaneous initiation of the muscles of the components; differences were attributed to distinct electromechanical delays and inertia of eye, head, and finger. Biguer, Problanc and Jeannerod (1984) have also suggested that having the head move freely enhances finger accuracy, but the extent of the free head movement is not critical.

Carnahan and Marteniuk (1991) investigated a task in which participants were required to point to a target in two situations: pointing only with eye and head and pointing with the finger. Pointing velocity (fast vs. accurate) and pointing eccentricity (26 vs. 43 deg) were also manipulated. They found that timing between the eyes and head was altered significantly when hand movements were added to the system, from the eye pointing to the finger pointing condition. This may be due to some sort of head and arm synergy and postural disturbances caused by extending the arm (Carnahan, 1992; Carnahan & Marteniuk, 1994). The initiation of eye, head, and hand movements presented a variable pattern across fast and accurate conditions and 26 deg vs. 43 deg target eccentricity conditions (Carnahan & Marteniuk, 1991). In the fastest condition, the eyes and head started to move simultaneously and before the finger pointed to a target at 26 deg. However, when pointing at targets at 43 deg, the head started to move first, the finger was second and the eyes last. In accurate conditions and the target at 26 deg, the eyes started first followed by the head and finger. Conversely, when pointing to target at 43 deg, the eyes and head started to move at the same time and prior to the finger. Over most conditions a consistent pattern emerged. Eyes reached the target first followed by the finger and then the head. Moreover, the eyes reached the target at least 200 ms before the finger, regardless of the initiation pattern. Similar results have also been reported when manipulating variables such as speed and accuracy requirements, target eccentricity, and target movement (Carnahan, 1992).

Sharp and Whiting (1975) studied how eyes and head moved to acquire visual information in a one-handed catching task. The velocity of the ball was manipulated so participants had less time to see and catch the ball as velocity increased. They found that performance improved discontinuously with the allowance of longer viewing durations. Performance levels of catching improved gradually to durations up to 245 ms, remained stable from 245 to 365, and improved again up to 445 ms. Interestingly, the manner in which visual information was acquired through eye and head movements also changed in these intervals. For durations of less than 245 ms, visual information was obtained by maintaining eyes and head motionless and having the image of the ball moving across the retina (image-retina system). For durations of more than 365 ms, information was obtained by moving eyes and head to maintain the ball image relatively at the same place on the fovea (eye-head system). Between 245 and 365 ms, when the performance levels were stable, there was a transition phase during which the eye/head system gradually took charge of collecting the information.

Montagne, Laurent, and Ripoll (1993) reproduced the experiment of Sharp and Whiting (1975) with additional variables. In one of their experiments, they manipulated the type of gaze and head behaviour participants used. Participants had to track the ball, or to "anchor" their eyes on a diode at 0 deg or 33 deg from ball trajectory, in a protocol with four levels of ball flight duration (260 to 370 ms). They found that the percentage of successful trials decreased significantly in the two most constrained ball flight conditions, especially for the 33 deg anchoring.

Effects of target eccentricity on temporal costs of point of gaze and hand in aiming have been assessed by Helsen, Starkes and Buekers (1997). Subjects moved the eyes, head, trunk, and hand freely to predictable targets at eccentricities of 35, 40, and 45 cm. Given that the head could move freely, the visual angle between the home position and target button varied according to the participant's eye-to-button distance (e.g., 40 deg of visual angle for 55 cm, measured from an imaginary point halfway between the eyes when participants were looking straight ahead). It was found that point of gaze arrived on target in advance of the hand in approximately 50% of the response time of the hand. This 50% proportional time was considered an important emergent invariant characteristic not related to movement planning. With increasing target eccentricity, a significant increase in initiation time of point of gaze occurred but not of the hand. In a similar paradigm, Helsen, Elliot, Starkes and Ricker (1998) showed results confirming this invariant. A temporal coupling was found between completion of the primary eye saccade and the time for peak acceleration for the limb. Also, peak hand velocity coincided with completion of 50% of the total movement distance.

In summary, eye-head-arm coordination studies have focused mainly on a temporal description of movement initiation order and explored variables such as target velocity and eccentricity to near target locations. That is, assessments have been based upon subjects responding to targets within the reach of the hand. In the current study, both near and far targets were used. The near target was a ball, which had to be contacted by the bat, while the far target was the target area on the other side of the table to which the ball was directed. The presence of both near and far targets, which is a characteristic of many skills, such as tennis return, billiards stroke, and baseball hitting, potentially command the perceptual, cognitive and motor resources of athletes and study participants. To understand the visuo-motor demands during such skills, a review of visuo-motor coordination in the context of visual search follows.

Visual Search and Expertise in Sport

Due to their complex and constantly changing conditions, many sports require rapid decisions from performers. Focusing attention on the most relevant sources of information and knowing "where" and "when" to look are critical aspects of skilled performance. The visual search patterns of expert performers are not conducted in a random manner but organized by perceptual strategies (Williams, Davids & Williams, 1999). Eye movements are controlled by a search strategy, which enables a more efficient use of the time available for analyses of the scene. Visual search processes involve using vision to acquire information from the environment in order to determine what to do in a given situation (Magill, 1993). The applicability of the current visual search literature can be questioned in regard to its ecological validity (Williams, Davids & Burwitz, 1994). Investigations reporting no expertise-related differences in visual search rates (e.g., Abernethy, 1991) typically require a passive viewing of pictures and videotaped displays and contrived, if any, motor responses. In contrast, studies that have recorded the gaze of experts and non-experts while performing specific motor skills have shown significant differences in gaze frequency, duration, and temporal control (Frehlich, 1997; Ripoll, Bard & Paillard, 1986; Vickers, 1996a).

Starkes (1993) discussed what differentiates experts from non-experts or novice individuals and made the following suggestions to improve expert-novice research methods.

> "First, it is necessary to design a series of representative tasks that capture the superior performance seen in the domain and elicit it under laboratory conditions. Second it is necessary to discover the mediating mechanisms of superior performance and analyze the types of learning and adaptation of the mechanisms that occur both in real world performance and the laboratory tasks" (p. 8).

Another criticism of the visual search research has been the focus on perception to the almost total exclusion of action. Researchers within ecological psychology state that perception and action should be viewed as mutually interdependent, reciprocally influencing each other (e.g., Savelsbergh & Bootsma, 1994; Turvey, 1977b). As a final point of criticism, visual search studies have focused on only a part of visual function, with little emphasis on the inter-relation between semantic and sensorimotor functions. Ripoll (1991) argued that the role of the semantic visual function is to identify and interpret the situation whereas the role of sensorimotor visual function is to carry out the visuo-motor response. Williams, Davids and Williams (1999) indicated that "the majority of research has only really addressed the semantic visual function in sport" and that researchers "should attempt to develop protocols which adequately simulate both semantic and somatosensory characteristics of the task" (p. 170).

Quiet Eye and Visuo-Motor Coordination

With the advent of mobile eye tracking systems, considerable progress has been made in understanding the coupling of visual and motor behaviour during the performance of skills as diverse as billiards (Frehlich, 1997), tennis (Singer et al., 1998), golf (Vickers, 1992); basketball (Vickers, 1996a), volleyball (Adolphe, Vickers & La Plante, 1997; Vickers & Adolphe, 1997), darts (Vickers, Edworthy, Rodrigues & Wagner, 1997, Vickers, Rodrigues & Edworthy, 1999), and rifle shooting (Vickers, Williams, Rodrigues, Hillis & Coyne, 1999). Three results have emerged consistently from these studies. During the preparation phase, expert motor performers, defined as those with excellent statistics during competitive performance of the skill, exhibit a more stable head, a lower frequency of fixation or tracking eye movements, and a longer duration of fixation or tracking to specific objects or locations in the task environment than these less skilled.

In this context, the notion of quiet eye (QE) has been defined by Vickers (1996a). QE is a measure of the location, onset, offset and duration of fixation or tracking gaze recorded while the participant is performing a motor or other skill (Vickers, 1996a). During QE, fixation or tracking is maintained on a specific location in space, with onset in advance of movement initiation. QE potentially serves as an objective indicator of visual attention when combined with concurrent measures of task performance.

QE has been found to have an optimal onset, offset and duration in motor skills such as the basketball free throw (Vickers, 1996a; 1996b), billiards, (Frehlich, Singer & Williams, 1998), darts (Vickers, Rodrigues & Edworthy, 1999), rifle shooting (Murray et al, 1999; Vickers, Williams, Rodrigues, Hillis & Coyne, 1999), and the volleyball serve reception and pass (Vickers & Adolphe, 1997).

When QE is experimentally reduced, motor performance has been found to decline for both experts and novices (Frehlich, 1997; Frehlich, Singer & Williams, 1998). When QE is trained, onset, offset and duration have been found to improve and performance accuracy has been shown to increase (Adolphe, Vickers & LaPlante, 1997; Harlee & Vickers, under review).

Vickers (1996a) compared basketball free throw shooters of two skill levels: experts (with success rate above 75% of their free throws) and near-experts (with success rate below 60%). She found that the experts initiated fixation on the hoop midway through the preparation phase and maintained fixation significantly longer than the near-experts. Most important was the duration of QE, defined as the duration of final fixation on a critical location prior to initiation of movement time (MT). QE for the expert shooters was 972 ms on hits, 806 ms on misses and less than 400 ms for the near-expert group, on hits or misses. QE was therefore related to the definition of reaction time, a period of time when critical visual information is obtained prior to movement initiation (Schmidt, 1988, 1991). Clearly, fixating the target early was important as was holding the gaze steady until the shooting action began.

In a study of Team Canada volleyball athletes who performed the serve reception and pass (Vickers & Adolphe, 1997), QE was defined as the duration of tracking on the ball prior to the first step taken by the athlete to play the ball. QE for the expert receivers (mean serve reception accuracy 65%) was 432 ms while the near-experts (mean accuracy 50%) did not exhibit a QE at all. The expert receivers did not begin stepping until after tracking the ball for almost half a second. The near-experts initiated their first step before the onset of tracking on the ball and often before the serve was delivered. Tracking onset was earlier and duration longer for the expert receivers than the near-experts. Neither group tracked the ball to contact, in agreement with previous studies (Bahill & LaRitz, 1984; Ripoll & Fleurance, 1988). Two associated motor characteristics of the near-experts included a higher incidence of corrective steps and more frequent reception of the ball at less than optimal locations. Both of these motor behaviours were associated with a failure to track the ball during early ball flight and thus anticipate the location and speed of the ball at contact.

Eye and Head Movements in Table Tennis

Ripoll and Fleurance (1988) analyzed the visuo-motor behaviour of expert table tennis players while performing three different strokes (forehand, forehand with top spin, and backhand drive). Results confirmed that experts did not necessarily track the ball throughout the entire trajectory. Players maintained tracking on the ball at the very beginning of the trajectory. Following this, the nature of tracking varied according to the type of stroke: the ball was tracked more often and for a longer period of time when it moved towards the midline of the body (backhand drive) than when it moved laterally in relation to the body (forehand and forehand with top spin drives). The gaze was also maintained on the ball during ball/bat contact when the ball was directed to the central location using an unpredictable spin serve. It appeared that visuo-motor behaviour was determined by external constraints on the stroke, such as ball trajectory eccentricity in relation to the mid-line of the body and the dynamics of ball contact on the bat that affected accuracy of the stroke.

Ripoll and Fleurance (1988) proposed a process of eye-head-arm coordination which occurs during the final portion of ball flight. Prior to final contact, between the bounce and the strike, the eyes were stable and aligned with the head orientation. Head and eyes were held in advance of the location of ball/bat contact. This occurred more frequently when the ball was projected laterally to the body (forehand and forehand with top spin drives) and mainly when the strike itself was particularly accurate (forehand with top spin drive). Kinematics of arm action was not recorded, and therefore, the coupling of the visual and motor systems could not be described.

Ripoll (1989) compared situations of table tennis drill (more predictable) and match (less predictable) and obtained three interesting results in a second study. Visual fixations on the participants' opponent were only systematic in the match situation. Only the first part of the ball's trajectory was tracked, with tracking onset immediately after the opponent's release of the ball regardless to the condition; visual tracking was more frequent and of longer duration in a match. Movement preparation (defined as backward arm movement swing) was longer in a match situation while the duration of execution phase (defined as forward arm movement swing) was unchanged.

Ripoll suggested that two distinct visual functions, semantic and sensorimotor, were operating across the range of skills studied. The role of semantic visual function was to identify and interpret the situation, whereas the role of the sensorimotor visual function was to carry out the response. In table tennis, semantic processes were responsible for picking up visual cues from the opponent and were used to predict behaviour and type of stroke being used. Sensorimotor processes were involved in estimating the time of contact needed to time the strike and to coordinate the visual and motor systems participating in the stroke (Ripoll, 1991). According to Ripoll (1991), semantic functions identified the visual cues and interpreted that information as the indication of an appropriate target area to which to respond while sensorimotor functions supplied continuous information for coordinating the visual and motor systems (eye, head, trunk, and arm) during all phases of the stroke.

Arm Coordination in Table Tennis

Bootsma and van Wieringen (1988) have described important timing characteristics of an attacking forehand drive in table tennis. Although they did not record eye and head movements directly, they did measure the time between the ball's approach and drive movement relative to monocular and binocular viewing conditions. Under binocular vision conditions, the sources used for timing the initiation of the drive were ball location and time in the frontal plane, the latter defined as time between the moment of initiation and the moment the ball crossed the frontal plane. Under monocular condition, drive movements tended to be slower. The consistency of the drive was higher under binocular condition while under monocular condition the subject adapted the drive to the very slight variations in time to the frontal plane.

Bootsma and van Wieringen (1990), in a further study of the arm action in table tennis, found that players did not fully rely on a consistent movement production strategy. The authors assumed that visual information to time their table tennis stroke was obtain through an optic flow variable called "tau". Tau, not a concept specific for table tennis, has been defined as the inverse of the relative rate of dilation of the closed optical contour generated by an object approaching, which specifies the time-to-contact between the observer and the object (Lee, 1976, 1980; Savelsbergh, Whiting & Bootsma, 1991). Bootsma and van Wieringen (1990) found that variability in response was lower at ball/bat contact than at initiation, suggesting that players adapted their timing to differing stroke demands early rather than later in the stroke. They argued that the optic variable tau was used to anticipate the movement of the ball and time the movement precisely at contact. Negative correlations between the perceptually specified time-to-contact at the moment of drive initiation and mean acceleration during the drive indicated functional trial-to-trial variation. These results led the authors to argue, in agreement with Ripoll and Fleurance (1988), that task constraints provide the organizing principles for perception and action; a mutual dependency exists between motor and perceptual components of complex motor skills such as table tennis.

Hypotheses

The present experimental situation measured participants' gaze and arm movements as they responded to a table tennis serve using a forehand stroke towards one of two cued target areas on the opposite side of the net. These measures were made for a low and a high skill group. Gaze behaviours measured were quiet eye (QE) tracking on the ball, tracking the ball during movement time (TMT), and eye-head stabilization (EHS) prior to ball-bat contact. Arm behaviour was accessed through the measures of movement time (MT) that corresponded to the period from the initiation of the forward phase of the arm to the ball-bat contact, and arm velocity at ball-bat contact (AVC). The amount of time available to detect a cue light and execute the arm action was manipulated. The cue that indicated the appropriate target (right or left) area to return the ball was delayed in three conditions: Pre-cue (PR), Early-cue (EA), and Late-cue (LA). The effects of skill level (high skill, HS; low skill, LS) and accuracy on the target (hits vs. misses) were also investigated.

Effects of Skill Level and Accuracy. Longer durations of tracking on the ball during volleyball reception and pass (Vickers & Adolphe, 1997) and longer durations of fixation on relevant locations (Vickers, 1996a) of expert compared to lesser-experienced players have been reported in the literature. Also, longer durations of stabilization of eye and head prior to ball release in basketball jump shot have been demonstrated (Ripoll, Bard & Paillard, 1986). More skilled participants present more efficient gaze behaviours than lesser-skilled ones (Williams & Davids, 1998) and consequently, obtain higher accuracy levels. In addition, participants (regardless of skill level) show that optimal gaze behaviour durations tend to generate more successful responses (Ripoll, Bard & Paillard, 1986; Vickers, 1996a; Vickers & Adolphe, 1997).

- The high skill group was expected to have significantly longer QE and EHS durations than the low skill group.
- QE and EHS durations were expected to be significantly longer during hits than during misses.
- The high skill group was expected to have significantly higher AVC than low skill group.

Effects of Cue Condition. The effects of visual cueing have not been previously investigated in such a natural, sport-related context. The expected decrease in accuracy can be justified by the speed-accuracy trade-off (Fitts, 1954), and well-documented consequences of time requirements possibly shorter than a visual reaction time (Carlton, 1981a). Similarly, the expected decreases in AVC and MT could also be linked to a reduction of time available.

In terms of gaze behaviour, a compensatory shift between ball tracking on the preparation phase and gaze stability during the execution phase was expected as the cue was more delayed. This suggests that participants would attempt to overcome the decrease in time available by tracking the ball less and maintaining stable gaze longer. Similar transitions in visual information pick-up, generated by different manipulations, have been reported by Sharp and Whiting (1975) and Montagne, Laurent and Ripoll (1993).

- Accuracy was expected to be significantly lower as the cue was more delayed.
- QE was expected to be significantly shorter as the cue was more delayed.
- EHS and TMT were expected to be significantly longer as the cue was more delayed.
- AVC and MT duration were expected to be significantly lower as the cue was more delayed.

Method

Participants

Sixteen adults volunteered for the study. Nine participants were classified a posteriori as high skill (HS) and seven as low skill (LS) based on their mean experimental accuracy scores. The high skill group was composed of one female and eight males with mean age of 27.9 years old (range 19 to 42). The low skill group was composed of two females and five males with mean age of 26.6 years old (range 21 to 32). Three male participants (two in the high skill group and one in the low skill group) were left-handed. All other participants were right-handed. Participants were recruited among University of Calgary Table Tennis Club members and University of Calgary students. All testing was conducted consistent with institutional guidelines for informed consent. Participants received a small honorarium for their participation.

All participants were given a visual screening test by an optometrist that included assessment of monocular far acuity. Uncorrected, high-contrast visual acuity was measured at 20 ft (6.1 m) using a Snellen chart. The high skill group had a mean visual acuity of 20/21 and 20/22, and the low skill group 20/43 and 20/23 for right and left eyes, respectively. The poor mean visual acuity for the right eye of the low skill group was due to one participant who had 20/200 in that eye. This participant was included in the experiment to estimate the possible effect of a functional monocularity in gaze and arm patterns during interceptive tasks. One participant (high skill group, whose uncorrected visual acuity was 20/25 and 20/30 for the right and left eyes, respectively) wore corrective contact lenses during data collection, which presumably improved acuity beyond the uncorrected levels. None of the other participants wore corrective lenses.

Apparatus

Vision-in-Action (VIA) System. The Vision-in-Action system (Vickers, 1996a, 1998a, 1998b) integrated a mobile eye tracker with an external camera that assessed participants' eye and body movements, a time code generator and two video mixers that coupled participants' gaze, motor and ocular behaviour in time. An Applied Sciences Laboratories 501 eye tracker was interfaced to an external video camera (Sony, Model TRV82) and two digital video mixers (Videonics, Model MX-1) to produce the frame of video data shown in Figure 1.

Figure 1. A frame of video recorded with the Vision-in-Action method (Vickers, 1996a) containing the eye image (A), the participant's view (B), and external view (C).

The eye image (A), which was recorded by the eye camera on the eye tracker, contains horizontal and vertical axes at pupil and corneal reflection centroids. The corneal reflection is the reflection of a small helmet-mounted light source back from the surface of the cornea. The top portion of the frame (B) was recorded by the scene camera also on the eye tracker and shows the participant's location of gaze relative to the table tennis environment. Location of gaze is indicated by the white cursor. The bottom portion of the frame (C) shows the participant performing the table tennis task as recorded by the external camera. Video output frequency for Vision-in-Action system was 30 Hz (i.e., one frame every 33.33 ms).

The Applied Sciences Laboratories system 501, a monocular corneal reflection system, measured line of gaze with respect to the helmet. The helmet had a 10-metre cord attached at the waist, connected to the eye control unit, thus permitting the participant near-normal mobility. Miniaturized optics (scene and eye cameras), an illuminator, and visor were mounted on the helmet: their total weight was 700 g. By measuring both the pupil and the corneal reflection features and using parameters from a calibration procedure, this system could calculate line-of-gaze with respect to the helmet.

The eye camera, mounted on the top front of the helmet, was directed to the eye via the reflective visor with appropriate magnification so that the camera captured approximately a 1-in (2.54 cm) square around the eye (Figure 1A). The eye was illuminated by a near infrared light source that was beamed coaxially with the camera. The light from the illuminator, which was invisible to the participant, retro-reflected from the retina and produced an image of a backlighted bright pupil rather than a dark pupil. The reflected image of the light source from the corneal surface appeared as a very small spot that was even brighter than the pupil image. The video image was processed by a computer to identify and determine the centroids of the pupil and the corneal reflection. By measuring the vertical and horizontal distances between the two centroids and correcting for second-order effects, line of gaze with respect to the light source could be computed. The colour scene camera, mounted under the visor, recorded the reflection of the external side of the visor and showed the field of view in front of the participant (Figure 1B). This allowed free movement of the head, as found in regular table tennis play. The vertical field of view is 40 deg and the horizontal field of view is 50 deg. A square cursor (representing 2 deg of visual angle with a 4.5 mm lens), indicated the participant's location of gaze in the scene was superimposed on the video image. The system has an accuracy of ± 1 deg of visual angle and precision of 1/2 deg. The Vision-in-Action system was used to maintain accurate calibration of eye movements during data collection.

Magnetic Head Tracker System (MHT). Interfaced to the Vision-in-Action system was a magnetic head tracker, developed by Ascension Technologies (Model Flock of Birds). The magnetic head tracker, a six degree-of-freedom measuring device, tracked the three-dimensional position and orientation of the eye tracker helmet relative to a transmitter. The transmitter was located above and behind the participant, as shown in Figure 2. Position and orientation were determined by transmitting a pulsed DC magnetic field that was measured by the receiver (attached to the top of the helmet). From the measured magnetic field characteristics, the receiver independently computed position and orientation of the head and made this information available to a host computer.

The magnetic head tracker has a static positional accuracy of 0.1 in (2.54 mm), a

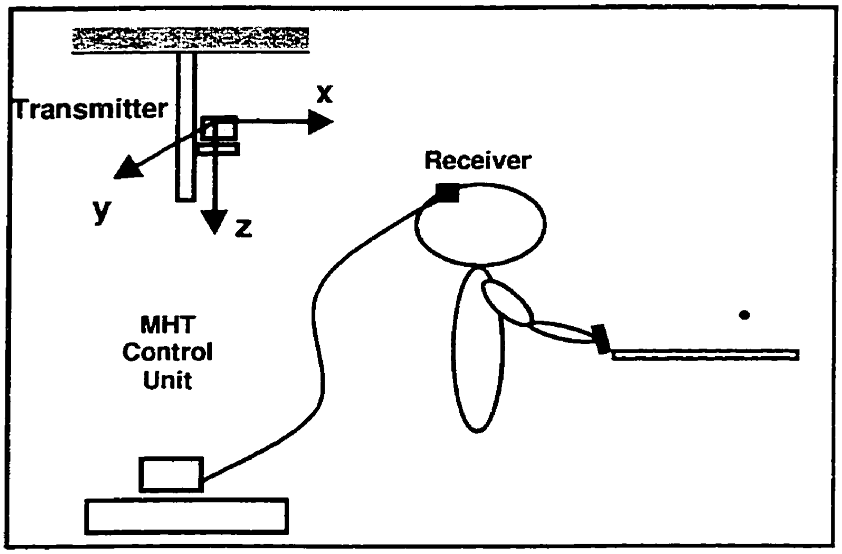

Figure 2. Setup of the magnetic head tracker (MHT) with transmitter, receiver and control unit.

positional resolution of 0.03 in (0.76 mm), a static angular accuracy of 0.5 deg, and angular resolution of 0.1 deg. Magnetic head tracker data were internally combined with the eye tracker data in order to generate the participant's line of gaze relative to the environment, rather than line-of-gaze related to the helmet. Eye-Head Integration is an expansion of the eye tracker software that enabled this combination. Eye-Head Integration data were updated at 60 Hz, the same frequency as the eye tracker.

The Eye-Head Integration software output the two-dimensional coordinates of the intersection point between the line-of-gaze and a plane of interest, defined in this study as the plane that coincides with the table tennis table surface. The Eye-Head Integration software also output three-dimensional position and orientation angles (azimuth, elevation, and roll) of the receiver with respect to the transmitter coordinate system.

The Motion Analysis System (MAS). The Motion Analysis system used six high-speed video cameras (set to 180 Hz) and a computerized system (EVa) that captured video images from each camera, recognized retro-reflective markers on each camera image, and reconstructed the three-dimensional position of the markers in the space. The EVa provided three-dimensional position data of arm and ball flight. The positions of each camera in the experimental setup are shown in Figure 3.

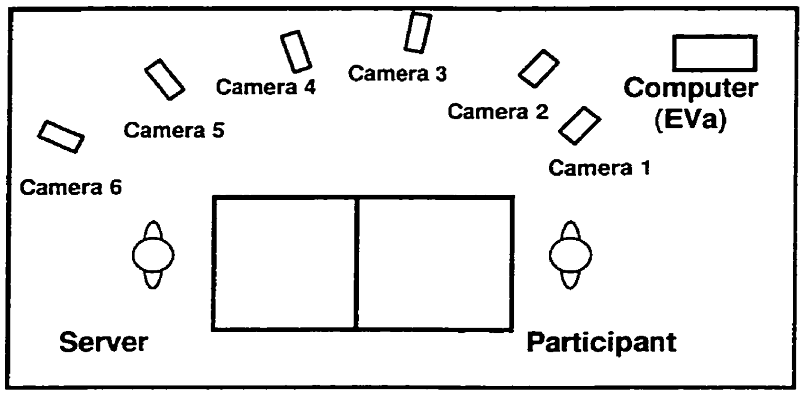

Figure 3. Top view of Motion Analysis system (MAS) setup showing the positions of six cameras, data collection computer, table tennis table, server and a right-handed participant.

As Motion Analysis system data processing has distinct phases, its accuracy was described in terms of the three-dimensional final measures of a known distance. A wand of 1 meter (1,000 mm) was recorded during one minute at 10 Hz as moving in a volume of 1.06 m X 3.46 m X 1.36 m. The obtained mean distance between the two markers on the wand was 1,000.1 mm (SD = 2.4).

Laser Device for Cue Activation. A laser device to detect the ball passage and activate one of the two sets of cue lights was placed in parallel alignment with the table tennis net (See Figure 4 below). On one side of the table, there were nine vertically arranged laser pointers attached to a height adjustable wood support. The distance between laser pointers was 3 cm. Nine corresponding receivers were placed on the opposite side of the table. Each laser pointer was aimed at its respective receiver, creating a laser "net". When the table tennis ball interrupted at least one laser-receiver communication, a box controlling all components activated randomly one set of cue lights. At the same time a signal was sent to the computer running Eye-Head Integration software and recorded as external data.

There was a set of three red cue lights for each target area. The distance between the lights in each set was 31 mm and the diameter of each light was 6 mm. The nominal luminance of each light, measured with a Minolta LS-110 Luminance Spot Meter, was between 2,300 and 2,500 cd/m^2.

Synchronization. Motion Analysis system and Eye-Head Integration software (combining eye tracker and head tracker data) data collection was synchronized by having electrical pulses sent simultaneously to both systems. The experimenter controlled the starting of data collection by pressing one key in a control unit. Each system was set to start data recording according to this external trigger.

Procedures

Calibration. Motion Analysis system calibration occurred before and after each data collection session. To calibrate this system, a metal cube with eight reflective markers was recorded by six cameras. EVa measured the same markers from each camera image and generated coefficients that showed the spatial relation between video images and the "real" space occupied by the cube. These coefficients were also used during the later three-dimensional reconstruction of the task. An additional calibration procedure was used due to the relatively large volume in which the ball traveled and participants performed. A metal wand with accurately measured markers on its ends was recorded in different orientations to increase the volume calibrated.

Eye and head tracker calibration procedures were fully integrated through the Eye-Head Integration software. Eye-Head Integration calibration was divided into specification of planes and specification of eye position in space. The planes to be specified to the software in this study were the table tennis table plane and the calibration plane (plane placed on the table surface). This was done using a receiver in a wand with a laser pointer at one end and a gimbal attached to the other. The gimbal allowed motion of the wand in three dimensions relative to the centre of the transmitter, the origin of the magnetic head tracker coordinate system. By pointing the laser spot in three points of each plane and by using previously measured distances from the transmitter to those same points, the Eye-Head Integration software calibrated the receiver signals to the three dimensional space in which the experimental task took place.

Before starting the specification of eye positions, the receiver was removed from the wand cup and placed on the top of the helmet and the specification of planes taken. The participant was fitted with the eye tracker helmet, followed by setup of eye camera, scene camera, and visor oriented to the table. The participant was then positioned in front of the calibration plane that contained nine points. While holding the head stable and moving only the eyes, the nine target points were defined in video coordinates in the scene monitor coinciding with those on the table. As the participant looked at each of the nine points, his or her eye position was recorded. This part of calibration took less than one minute in total. Final calibration for three defined locations on the table tennis surface (coinciding with ball trajectory) also took place before each trial to ensure maintenance of calibration. The duration of fine calibration was approximately 10 seconds.

Experimental Task. Figure 4 shows the experimental set-up that contained a regulation table tennis table, fitted with two sets of cue lights and two target areas. The participant was required to return the ball as accurately and as quickly as possible to one of two target areas (right or left). The target was cued by a set of lights interfaced to a laser device. Each serve-return pair was considered to be a trial. Target areas were rectangular (65 cm deep x 40 cm wide) placed on each corner of the server's side of the table and corresponded to those found effective in competition. The server was experienced in table tennis and was instructed to serve the ball to the same location using the same action and velocity for each serve. The ball was always served to the side of the receiver's referred hand (i.e., to the right side for right-handed participants and to the left for left-handed participants) who then responded with a forehand drive. The time at which the target area was cued relative to the serve was controlled to produce three distinct temporal conditions: 1) Pre-cue condition (PR) - the cue light was illuminated before the serve; 2) Early-cue condition (EA) - the cue was illuminated after the serve, in the initial part of ball flight. 3) Late-cue condition (LA) - the cue was illuminated after the serve, in the final part of ball flight (See experimental times of cue onset in the Results section).

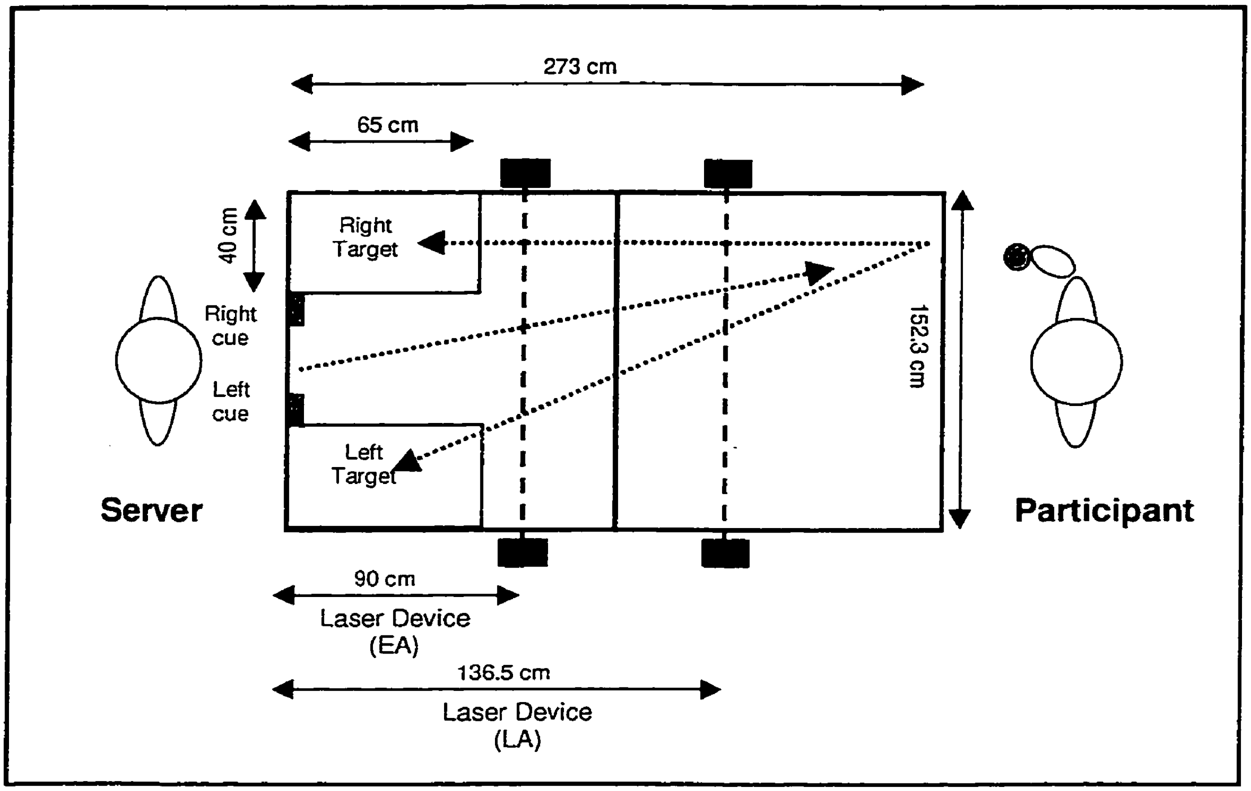

Figure 4. Representation (top view) of a right-handed participant in the experimental set-up, showing serve and possible return directions, target areas, right and left cue lights, and laser device positions for the Early-cue (EA) and Late-cue (LA) conditions with their sizes and positions.

The table tennis ball (diameter of 37.8 mm) was painted with a reflective liquid to be detected by the Motion Analysis system. The added weight to the ball created flight characteristics that were reported by participants to be slower than a regular ball. The balls used in the experiment weighed between 3.4 and 3.6 g as compared to 2.4 g of a regular table tennis ball. After a short practice phase, the participants reported successful adaptation to the added weight.

Data Acquisition Protocol. Participants were fitted with retro-reflective markers attached to the elbow (head of radius) and wrist (ulnar head) of their preferred hand to allow the digital processing of marker recognition in the Motion Analysis system. After a ten-minute warm-up with the server, they were then tested under one control and three experimental cue conditions. Trials were recorded until participants had obtained five hits and five misses in each cue condition, with a limit of recording 40 trials per condition. "Catch" trials were randomly placed during data collection. In a catch trial, the cue was not presented and participants were previously instructed to not respond to the serve. Catch trials were used in order to avoid guessing regarding the cue (Davids, 1988; Schmidt & Lee, 1999).

During the control condition (baseline), the participant's accuracy was assessed without the eye tracker in the Pre-cue condition. Participants were then fitted with the eye tracker and calibrated to perform in three experimental cue conditions (Pre, Early, and Late-cue). To minimize order effects, tasks orders for the three experimental conditions was assigned using a Latin square design (Maxwell & Delaney, 1990). The total time to complete all conditions was approximately 45 -60 minutes.

Data Analysis. The Eye-Head Integration software provided data for the horizontal and vertical gaze (table coordinate system) and three-dimensional position and orientation of head (transmitter coordinate system); the Motion Analysis system provided the three-dimensional positions of the elbow, wrist, and ball (calibration cube coordinate system). A program written in Matlab language specifically for the present study was used for data smoothing, interpolation, coordinate system transformation and calculation of angles of interest. Elbow, wrist, head position and head orientation data were smoothed with a fourth-order Butterworth filter at 5 Hz. Ball position data were smoothed with the same filter at 30 Hz.

To match the frequency of the Motion Analysis system frequency, an interpolation procedure was used to transform the Eye-Head Integration data from 60 Hz to 180 Hz. Linear interpolation calculated the new gaze data points to coincide with an imaginary line between each pair of original data points; this is appropriate for gaze data due to the speed and abrupt changes in eye position. Spline interpolation estimated new data points for head movement according to a smoother curve that fit the original data; this is appropriate for head data due to the relatively slow nature of head movements and their smooth trajectories.

To calculate the angles of interest, data in the table and the cube coordinate systems were transformed (translated and rotated) to the transmitter coordinate system shown in Figure 2. These transformations were applied using a Matlab routine based on Soderkvist and Wedin's (1993) algorithm to determine rigid body rotations and translations. To test the accuracy of these transformations, measurements of three points on the table (distant from each other) in the three coordinate systems were used: cube calibration (Motion Analysis system), table and transmitter (gimbal laser and ruler). The root mean squared value of residuals resulting of the transformation from cube to transmitter coordinate system was 0.81 cm, and from table to transmitter coordinate system was 0.96 cm. These transformations were then performed for all calibration settings.

Once all data were in the same coordinate system, three angles (Figure 5) were

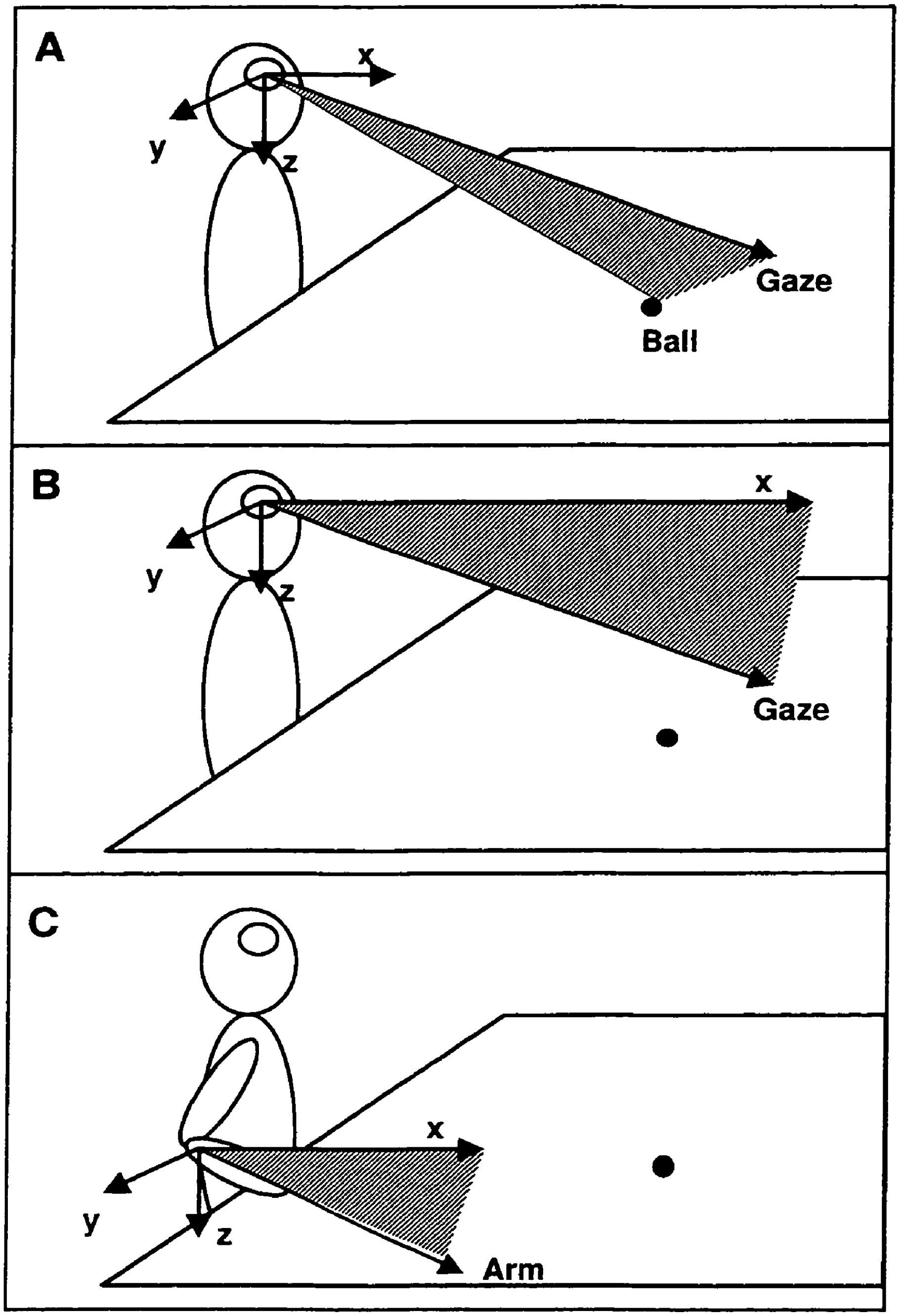

Figure 5. Representation of visual angle between line of gaze and ball edge (A), gaze and X-axis of the transmitter coordinate system (B), and the angle between arm (elbow-wrist segment) and X-axis of transmitter coordinate system (C).

calculated: visual angle between line of gaze and ball edge (A), visual angle between line of gaze and X-axis of the transmitter coordinate system (B), and the angle between arm (segment from elbow to wrist) and X-axis of the transmitter coordinate system (C).

Dependent Variables

Accuracy (percent). Accuracy scores were the percentage of accurate returns of the ball to the designated target area (hits).

Quiet eye (QE) onset, offset, and duration. QE was defined as the duration of final tracking on the ball prior to the initiation of arm forward phase (MT) (Vickers, 1996a). The criteria for QE were that the visual angle between line of gaze and ball edge (Figure 5A) should be maintained for at least 100 ms within three degrees. A value of three degrees was used for ball tracking based on precedents in the literature (Bahill & LaRitz, 1984; Ripoll & Fleurance, 1988; Vickers & Adolphe, 1997), as well as those for parafoveal tracking (Carpenter, 1988).

Tracking during movement time (TMT) onset, offset, and duration. TMT was defined as the duration of tracking on the ball during the arm forward phase (MT). The criteria for TMT were the same for QE except that it should be initiated during MT.

Eye-head stabilization (EHS) onset, offset, and duration. EHS was defined as the period of stable alignment of the eye and head before ball-bat contact (Ripoll & Fleurance, 1988). The criteria for EHS was that the visual angle between line of gaze and the X-axis of the transmitter coordinate system (Figure 5B) should remain stable in the final part of ball flight. Stability was based on a fixation criterion, adapted from Helsen et al. (1998). The onset of EHS required that this angle should be maintained with a standard deviation of 1 deg or less for at least 50 ms. If this criterion were satisfied, EHS was considered to have started with the first of those samples. The offset of EHS would occur when four sequential gaze angle samples (approximately 22 ms) were all farther away than 1.5 deg from the mean value of the angles within that period of stabilization.

Movement time (MT) onset, offset, and duration. MT was defined as the duration of the forward phase of the arm movement until contact of the ball. The arm forward phase was used by Bootsma and van Wieringen (1988, 1990). Abrams, Meyer and Kornblum (1990) have defined this final phase when the movement is executed as the impulse phase. The forward phase was also selected because pilot data showed that some performers in table tennis did not have a backward phase. MT onset criterion was the greatest angle between arm (elbow-wrist segment) and X-axis of transmitter coordinate system (Figure 5C). This period of time was characterized by decrease of angular position as the arm moved forward. The ball-bat contact was determined during the three-dimensional reconstruction of ball movement in the Motion Analysis system. Contact was defined as the time of last data point before the ball exhibited an abrupt change in the direction of its trajectory, which was obtained from the three-dimensional coordinates of the ball.

Arm velocity at contact (AVC). AVC was defined as the angular velocity between arm (elbow-wrist segment) and X-axis of transmitter coordinate system (Figure 5C) at the moment of ball-bat contact. Bootsma and van Wieringen (1988) have used a similar measure.

Figure 6 shows an example output of the data processing from one trial. The plots

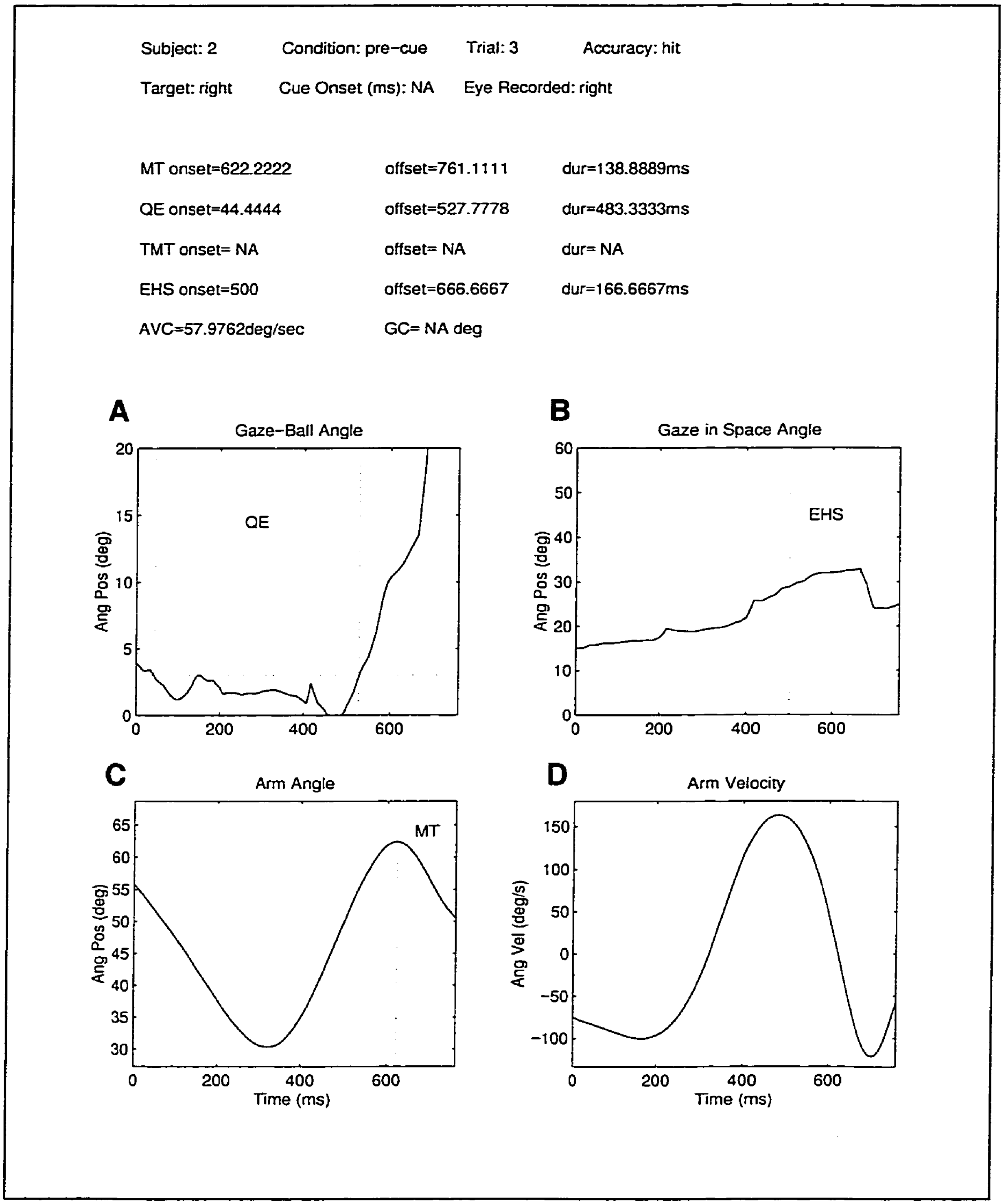

Figure 6. Example of output data for one individual trial with identification information, values for all dependent variables (top), and plots that originated the values of QE (A), EHS (B), and MT (C) onset, offset, and duration, and AVC (D).

of visual angle between line of gaze and ball edge (A), gaze and X-axis of the transmitter coordinate system (B), angle between arm (elbow-wrist segment) and X-axis of transmitter coordinate system (C), and arm velocity (D) during the trial are presented. Also, values for all dependent variables that were obtained by the Matlab program are shown.

Absolute time values (ms) are shown in Figure 6. Because the duration of each trial and component within a trial varied, a normalization procedure was applied to data and times relative to total trial duration (%) obtained. Thus, every trial had its onset transformed to 0 % (serve), its offset to 100% (ball-bat contact), and each point in time represented a proportion to the total time (Schmidt & Lee, 1999). The normalization of time of each data point was proportionally calculated using the following formula:

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

Analyses were carried out for absolute and relative times. Absolute time is normally used to discuss limitations in terms of information processing and minimal requirements of time during performance. Relative time description preserves the characteristics of each investigated behaviour with respect to the specific time available in each particular trial.

<u>Independent Variables</u>

<u>Skill level.</u> Two skill level groups (high skill and low skill) were defined post hoc based on participants' overall accuracy on the experimental task during the control and

experimental conditions.

Cue Condition. Three experimental cue conditions (Pre, Early, and Late-cue) were based on manipulation of cue onset time.

Accuracy. Data were collected for hits and misses allowing a comparison of the dependent variables for differing levels of accuracy.

Trials. Five trials (t1, t2, t3, t4, and t5) were collected for each cell of the design, providing information on possible changes within each level of cue condition and accuracy. Trials effects are usually interpreted as occurrence of learning or fatigue during the experiment.

Results

Ball Flight

Ball flight characteristics analyzed were direction of serve (DS), flight time to the second ball bounce (B2), and total flight time (FT). The direction of serve was defined by the angle between a line passing through the ball position at serve and contact points on the horizontal plane and the X-axis of transmitter coordinate system. The flight time to the second ball bounce was measured form the time of the serve. Total flight time was the duration of ball flight time from serve to contact.

A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA, with repeated measures on the last three factors, was conducted on direction of serve data. An alpha level of .05 was set for this and all subsequent statistical analyses. No significant main effects or interactions were found for direction of serve (Table 1). The same ANOVA on second ball bounce data (milliseconds and percent) revealed that second ball bounce (ms) occurred significantly earlier for high skill ($\underline{M}$ = 569.3 ms, $\underline{SD}$ = 43.8) than for low skill participants ($\underline{M}$ = 604.2 ms, $\underline{SD}$ = 35.2), $\underline{F}(1, 112) = 10.82$, $\underline{p}$ = .005, indicating that the server tended to use slightly faster serves when participants were of high skill. The interaction Trials X Skill also reached significance, $\underline{F}(4, 112) = 2.66$, $\underline{p}$ = .04, although the pattern across trials was not systematic. The second ball bounce (percent) was also significantly affected by cue condition, $\underline{F}(2, 112) = 15.72$, $\underline{p} < .001$. This difference seemed related to the participants' delay to hit the ball in the harder cue conditions (see MT results below) because the second ball bounce in percent is obtained relative to the total flight time. No other main effects or interactions were significant.

Table 1 shows the mean values of second ball bounce for high and low skill groups during hits and misses during the three cue conditions.

Flight time data were analyzed in the same manner as direction of serve and second ball bounce. Although other main effects and two-way interactions reached statistical significance, they were embedded in three-way interactions. The interaction of Cue Condition X Trials X Skill, $\underline{F}(2, 112) = 2.29$, $\underline{p} < .03$, was significant for flight time. The low skill group increased ball flight duration from the second bounce to contact by delaying movement time, a strategy more apparent in trial 3 (t3), than in early (t1, t2) or late trials (t4, t5). The interaction Cue Condition X Accuracy X Trials, $\underline{F}(8, 112) = 3.43$, $\underline{p} < .02$, was also found significant for flight time, but without a clear pattern of change across trials. No other interactions and main effects were significant, including the Cue Condition x Accuracy x Trials x Skill Level interaction.

Even though differences on second ball bounce data in ms (purely affected by the server action), second ball bounce data in percent, and flight time data in ms (also affected by participants' actions) were present, the patterns of ball flight produced by the server were quite consistent. This is shown in Table 1, which summarizes the means of ball flight characteristics by skill level, cue condition and accuracy. Note also that the trials (t1 to t5) in each level of the independent variable accuracy occurred in distinct times during data collection due to the uncertain occurrence of a hit or a miss in a given trial. Thus, interpretation of any significant interactions involving trials effect should be done with caution.

Table 1. Mean (SD) direction of serve (DS), flight to second bounce (B2), and total flight time (FT) during hits and misses in the Pre-cue, Early-cue, and Late-cue conditions for high (HS) and low skill (LS) groups.

		Pre-cue		Early-cue		Late-cue	
		Hits	Misses	Hits	Misses	Hits	Misses
	DS (deg)	10.1 (3.7)	10.3 (2.7)	9.9 (3.1)	10.4 (3.4)	10.2 (3.3)	9.8 (2.8)
	B2 (ms)	568.5 (38.1)	563.7 (37.1)	561.8 (39.2)	571.3 (36.4)	568.3 (35.0)	582.5 (67.2)
HS	B2 (%)	72.0 (5.3)	73.0 (4.2)	71.2 (5.0)	71.6 (5.7)	67.8 (4.8)	69.5 (6.3)
	FT (ms)	759.5 (49.9)	749.0 (59.1)	753.0 (56.1)	765.0 (70.4)	812.7 (68.7)	813.3 (68.2)
	FT (%)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)
	DS (deg)	10.9 (2.4)	10.3 (2.0)	9.9 (3.0)	10.3 (2.3)	10.1 (2.3)	10.0 (2.5)
	B2 (ms)	600.5 (35.7)	596.0 (37.6)	610.3 (31.9)	604.8 (36.2)	613.6 (37.2)	600.0 (31.3)
LS	B2 (%)	73.4 (3.9)	74.6 (4.8)	72.7 (3.6)	71.4 (3.4)	71.6 (4.8)	71.0 (3.8)
	FT (ms)	790.7 (40.4)	773.5 (53.9)	812.9 (38.9)	819.7 (47.1)	832.5 (66.4)	818.7(43.2)
	FT (%)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)

Cue Onset Times

Trial onset occurred as the ball was contacted during service. Cue onset time in the Pre-cue condition was estimated from the video VIA data through frame-by-frame analysis, as it occurred before trial onset. Mean Pre-cue onset was 1,620 ms (SD = 367) before the serve. A skill (2) by cue condition (2) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on the cue onset time data for Early and Late-cue conditions. It showed that cue onset time differed significantly across cue conditions as planned, but not due to any other main effect or interaction. This result confirms the consistency of ball flight characteristics because the ball activated the cue in the Early and Late-cue conditions. Cue onset time in the Early-cue condition was 263 ms (SD = 24.0), which represented 33.3% (SD = 2.7) of flight time. Cue onset time in the Late-cue condition was 492 ms (SD = 42.3), 60.3% (SD = 4.6) of flight time. These cue onset time data were used to calculate the time intervals between cue onset and the participant's ball-bat contact. These intervals indicate that participants had a mean of 2,366 ms, 521 ms, and 327 ms to detect the cue light and hit the ball during Pre, Early, and Late-cue conditions, respectively.

Determining Skill Groups (High Skill and Low Skill)

Two skill groups were determined a posteriori based on accuracy across all four testing conditions (one control and three experimental). Two skill groups were apparent, those with accuracy scores above 40% (high skill) and those below (low skill). High skill group's mean accuracy was 52.9% (SD = 14.9, range 43.6% to 67.8%), and low skill group's was 31.5% (SD = 12.9, range 29.7% to 35.6%), as summarized in Table 2.

Effect of Wearing the Eye Tracker

A one-way ANOVA (2) was conducted on accuracy data (percent) with and without the eye tracker. It revealed that wearing or not wearing the eye tracker (without, with) did not affect significantly the performance of either group, $F(1, 15) = .12$, $p = .73$. Mean accuracy without the eye tracker was 48.9% (SD = 17.7) and with it was 47.6% (SD = 15.65), as shown in Table 2. High skill mean was 61.3% (SD = 12.2) without the eye tracker and 55.5% (SD = 13.9) with it; low skill mean was 32.9% (SD = 7.5) without the eye tracker and 37.6% (SD = 12.0) with it.

Accuracy by Cue Condition

A one-way ANOVA (3) for the three cue conditions was conducted on accuracy data (percent). It revealed a significant effect of cueing, $F(2, 47) = 6.53$, $p = .003$, which

Table 2. Accuracy (percentage of hits, all trials included) of high skill (N = 9) and low skill (N = 7) participants during Pre (without and with eye tracker), Early and Late-cue conditions.

Condition		Pre-cue		Early-cue	Late-cue	
Eye Tracker		Without	With	With	With	M (SD)
HS	H1	58.3	33.3	53.3	53.9	49.7 (11.1)
	H2	57.1	64.7	58.3	31.3	52.9 (14.9)
	H3	73.9	61.1	70.0	30.0	58.8 (19.9)
	H4	55.2	47.8	45.2	46.4	48.6 (4.5)
	H5	45.8	52.4	60.0	18.2	44.1 (18.2)
	H6	44.4	50.0	46.7	33.3	43.6 (7.2)
	H7	79.4	79.2	55.6	57.1	67.8 (13.3)
	H8	66.7	66.7	73.9	50.0	64.3 (10.1)
	H9	70.6	42.9	46.1	26.1	46.4 (18.4)
LS	L1	27.8	50.0	35.0	16.2	32.2 (14.1)
	L2	45.5	47.1	23.8	17.7	33.5 (15.0)
	L3	35.3	37.5	29.6	22.2	31.2 (6.8)
	L4	33.3	33.3	15.0	9.8	22.9 (12.9)
	L5	37.0	13.8	50.0	41.7	35.6 (15.5)
	L6	30.0	42.9	47.1	22.2	35.5 (11.5)
	L7	21.7	38.9	50.0	8.1	29.7 (18.5)
	M (SD)	48.9 (17.7)	47.6 (15.6)	47.5 (15.7)	30.3 (15.6)	43.5 (17.6)

was followed up by examining the three possible pairwise comparisons for cueing condition. A Bonferroni adjustment of probabilities for multiple comparisons was used and, therefore, each comparison was tested using an alpha level of .0167 (i.e., .05/3). Late-cue levels of accuracy (M = 30.3%, SD = 17.3) were significantly lower than the Pre-cue (M = 47.6%, SD = 15.6), $F(1, 31) = 9.92$, $p = .004$, and Early-cue ones, $F(1, 31) = 9.72$, $p = .004$, as shown in Figure 7. Accuracy levels did not differ significantly between Pre-cue and Early-cue.

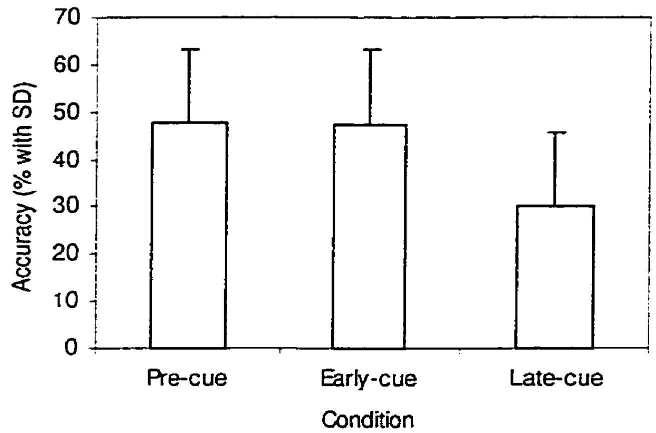

Figure 7. Accuracy (%) during Pre-cue, Early-cue, and Late-cue.

Biomechanical Analysis of Gaze, Head, and Arm Movements

The biomechanical description of visual and motor behaviour in the present study was based on the following aspects:

1.) The kinematics of line-of-gaze, head, and ball described the participants' ability of tracking an approaching ball and maintaining head and gaze stable in the horizontal and vertical directions.

2.) The distance between ball direction and head (named distance "d", measured in a top view - X-Y plane - perpendicularly to the direction of ball approach) provided an additional information on how participants controlled their whole-body position with respect to the ball during the hitting action. The physical size of participants could have affected the mechanics of hitting the ball and so, to account for this sort of individual difference, the distance d data were normalized by each participant's arm length (distance between elbow and wrist markers).

3.) Linear and angular position, velocity, and acceleration of the arm characterized how participants hit the ball. The X-Y plane was used in the linear description because the arm movement in these axes was more representative in terms of lateral positioning (Y axis) of the bat to coincide with ball and forward motion (X axis) to direct the ball to the other side of the table. X-axis was the axis with greater magnitudes of arm motion as shown in the linear plots.

Figures 8, 9, and 10 show the effect of cue condition on the amount of movement of head and gaze. Generally, the later the cue light was presented the smaller the size of gaze and arm motion observed. In the Pre-cue condition (Figures 8A and 8B) head and gaze moved more smoothly during ball flight. In the Early-cue condition (Figures 9A and 9B) participants seemed to wait for the cue light presentation to start to move their gaze. In the late cue condition (Figures 10A and 10B), gaze and head movements were most restricted, showing the largest angular distance between ball and gaze in both horizontal and vertical directions at the moment of ball-bat contact.

The effect of cueing on the arm hitting action is shown on Figures 11, 12, and 13. The X-axis (Figures 11A, 12A, and 13A) and angular (Figures 11B, 12B, and 13B) sizes of the arm movement were also reduced, as the cue signal was delayed. The same trend was observed for the magnitudes of linear and angular velocity (Figures 11C and 11D, 12C and 12D, 13C and 13D) and acceleration (Figures 11E and 11F, 12E and 12F, 13E and 13F), with their peaks decreasing as the condition became harder to respond. Also, participants were able to accelerate earlier in the easier cue conditions. The normalized distance d (Figures 8C, 9C, and 10C) decreased from the serve to the contact

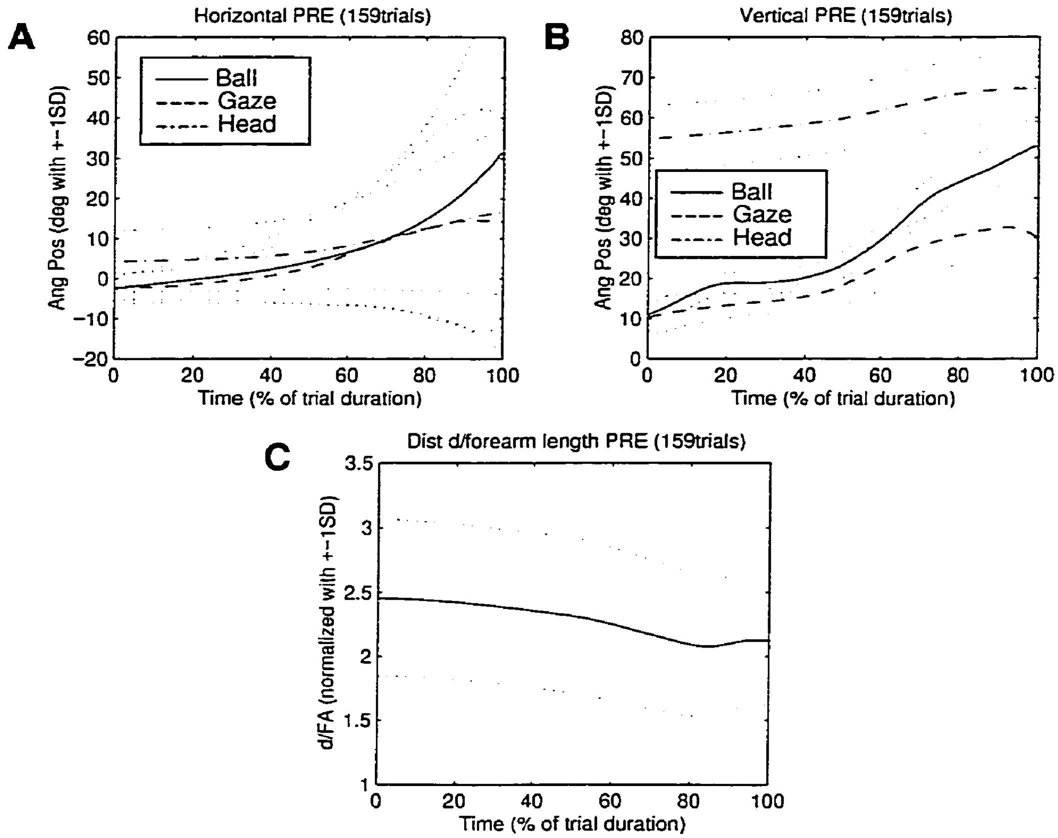

Figure 8. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) in the Pre-cue condition.

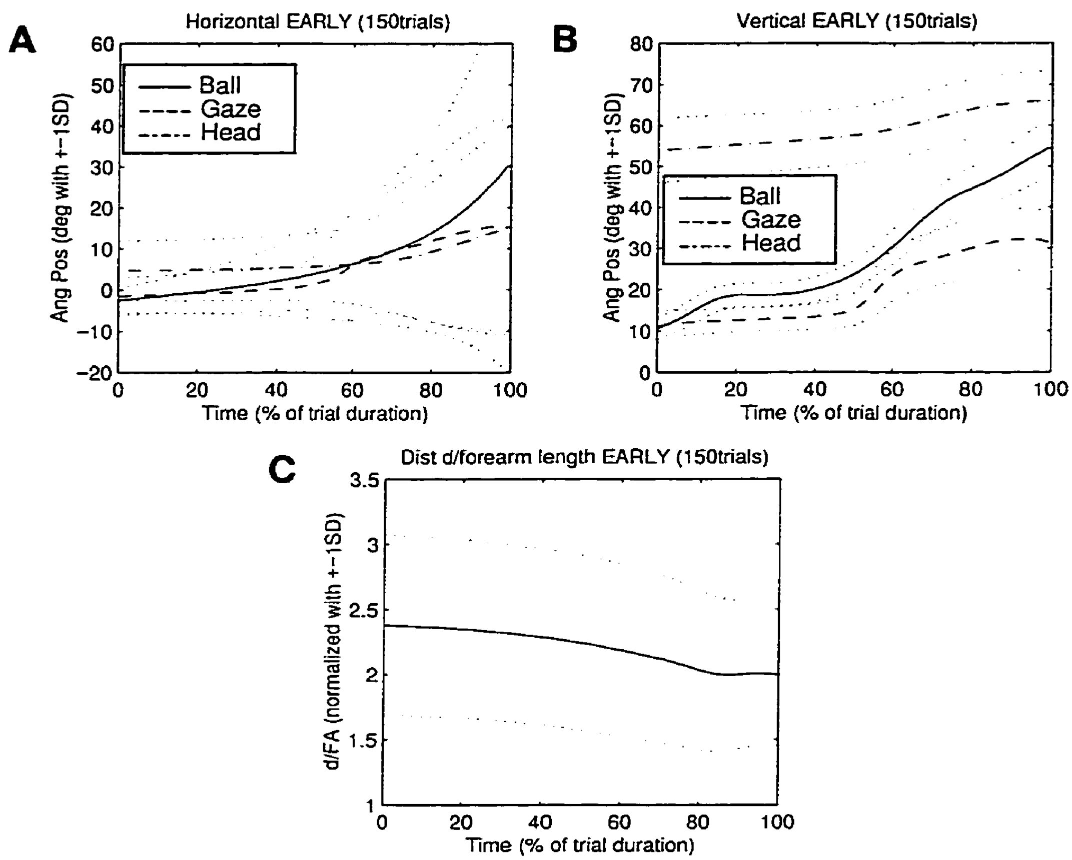

Figure 9. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) in the Early-cue condition.

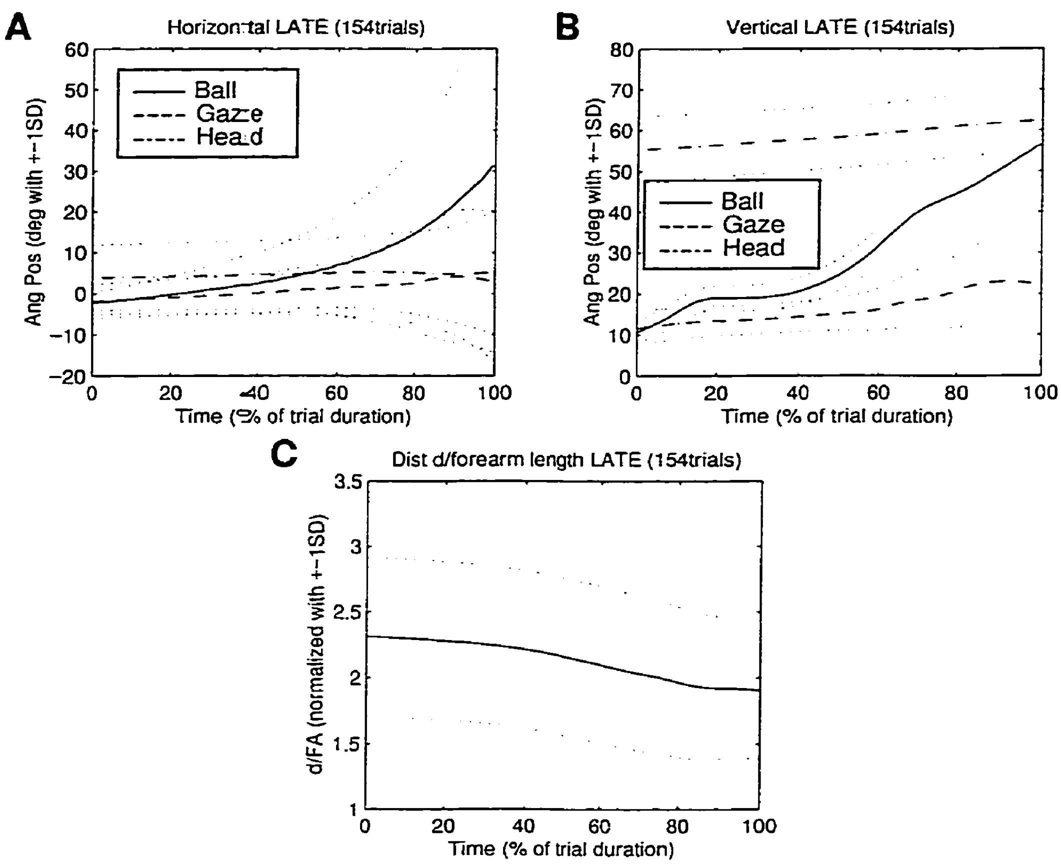

Figure 10. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) in the Late-cue condition.

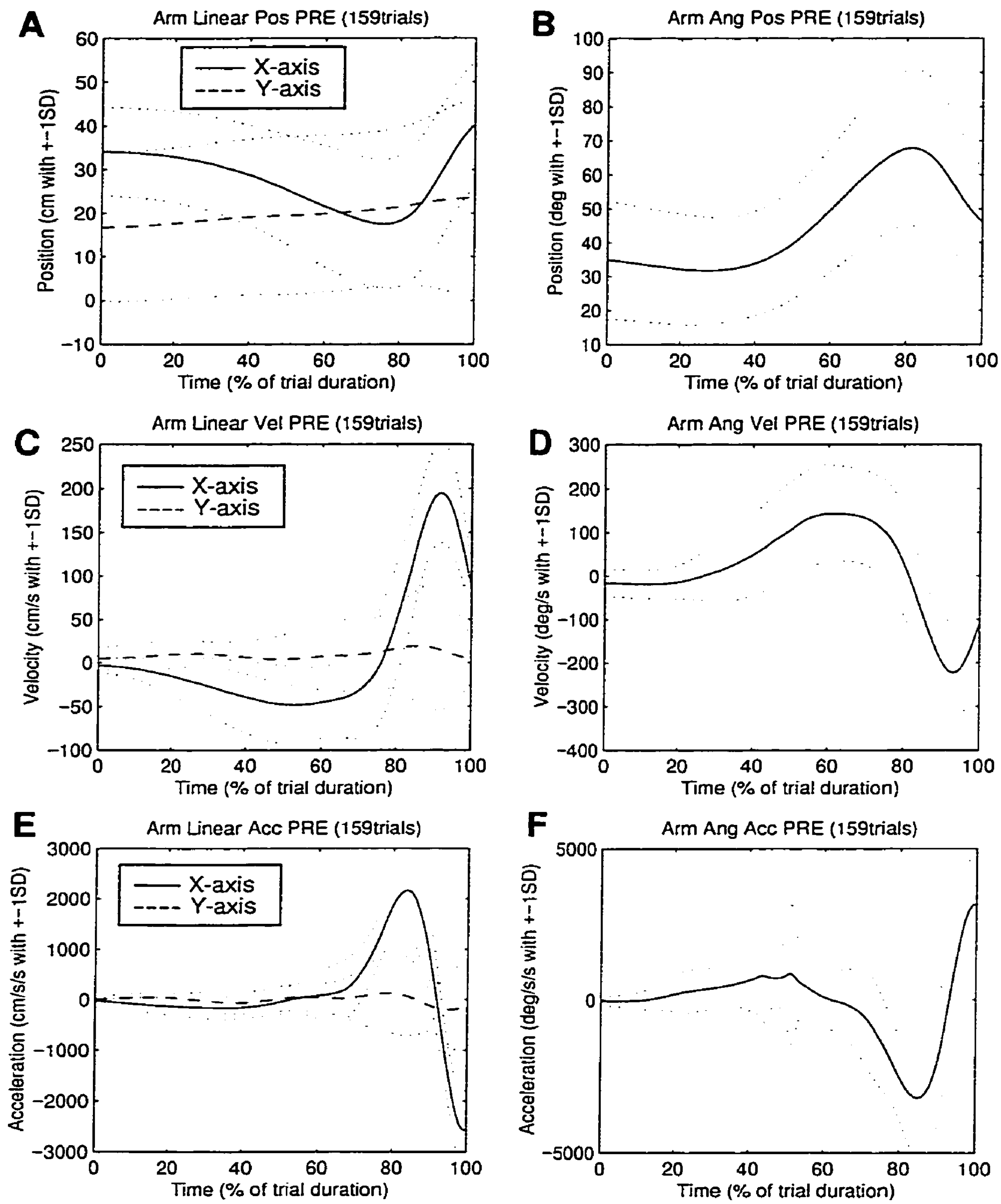

Figure 11. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) in the Pre-cue condition.

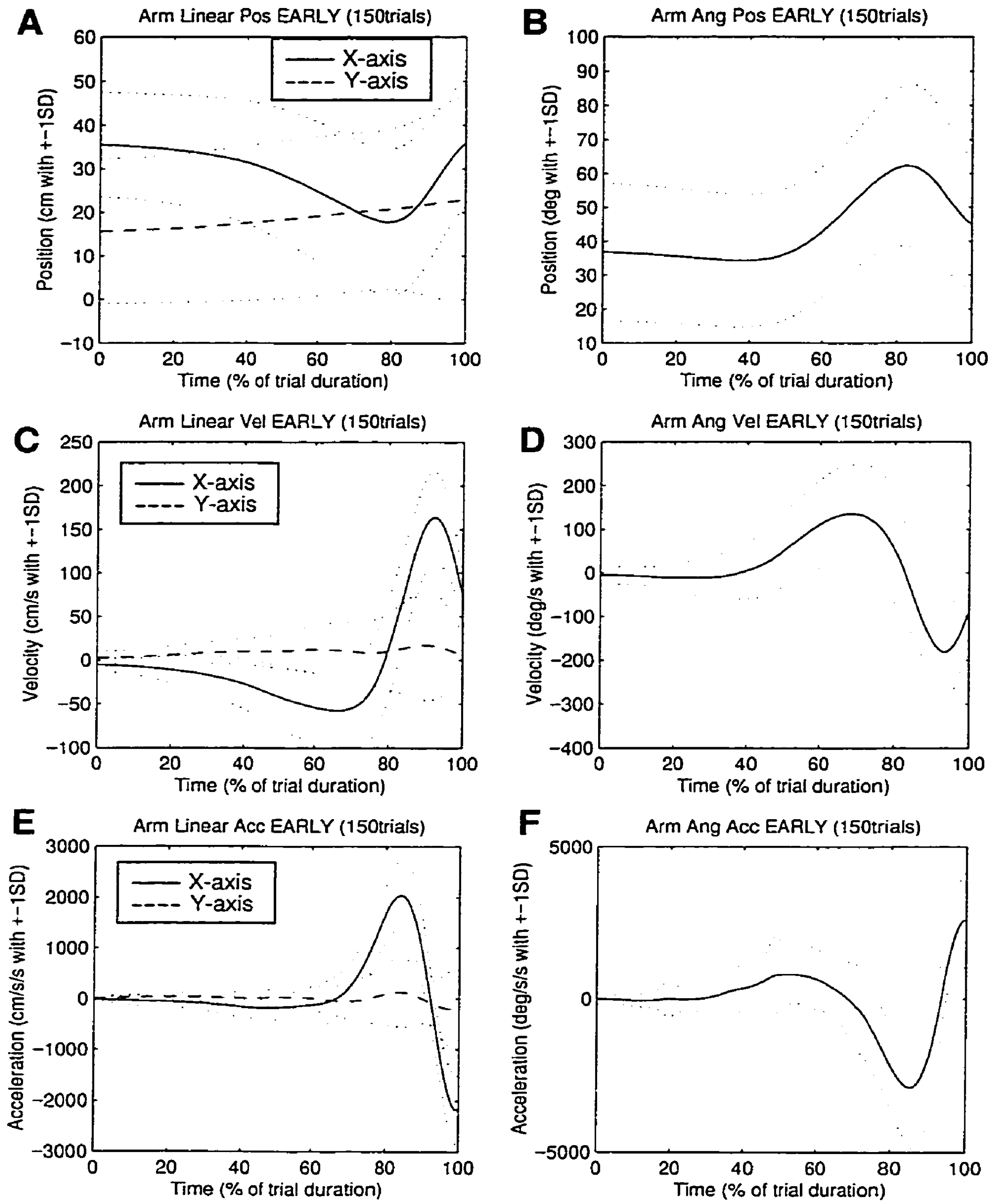

Figure 12. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) in the Early-cue condition.

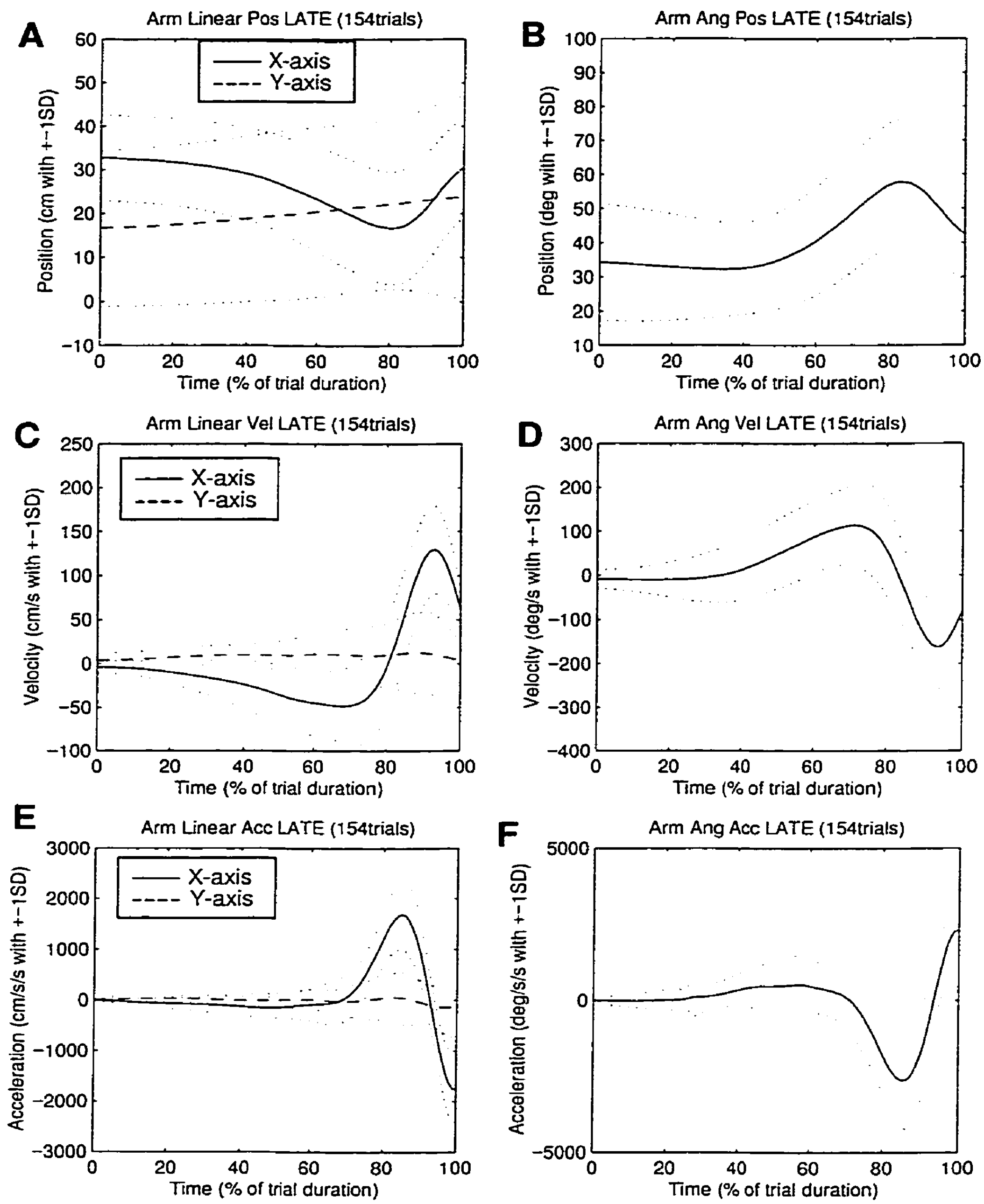

Figure 13. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) in the Late-cue condition.

moment within each cue condition. In addition to that, the distance d was slightly smaller as the presentation of the cue was delayed, showing a postural adaptation to maintain the head/trunk closer to the ball path during the entire trial duration.

Figures 14, 15, 16, and 17 present gaze and arm movements of high skill and low skill groups. The horizontal head movement differed between the groups. High skill participants (Figure 14A) had their heads directed towards the side the ball would arrive as the low skill participants (Figure 15A) kept their heads straight ahead in the beginning of the trial before starting moving laterally. Horizontal and vertical gaze and head movement plots revealed that in the final portion of ball flight the low skill group (Figures 15A and 15B) seemed to maintain gaze closer to the ball than the high skill group (Figures 14A and 14B) did. Low skill participants (Figure 15C) positioned themselves to keep shorten the distance of their heads for the ball's direction (the distance d) than the distance used by high skill participants (Figure 14C). This difference did not appear to cause an adaptation on arm linear kinematics as linear position, velocity, and acceleration plots of high (Figures 16A, 16C, and 16E) and low (Figures 17A, 17C, and 17E) skill groups were similar. Some differences in the angular arm movement of for the two skill levels were seen, however. High skill participants (Figures 16B, 16D, and 16F) moved their forearm further back before starting the forward phase and they also showed an earlier increase in angular velocity of the arm in the preparation phase than the low skill participants (Figures 17B, 17D, and 17F).

Figures 18, 19, 20, and 21 characterize examine pronounced differences in gaze and arm movements that occur when high skill participants the Pre-cue condition are

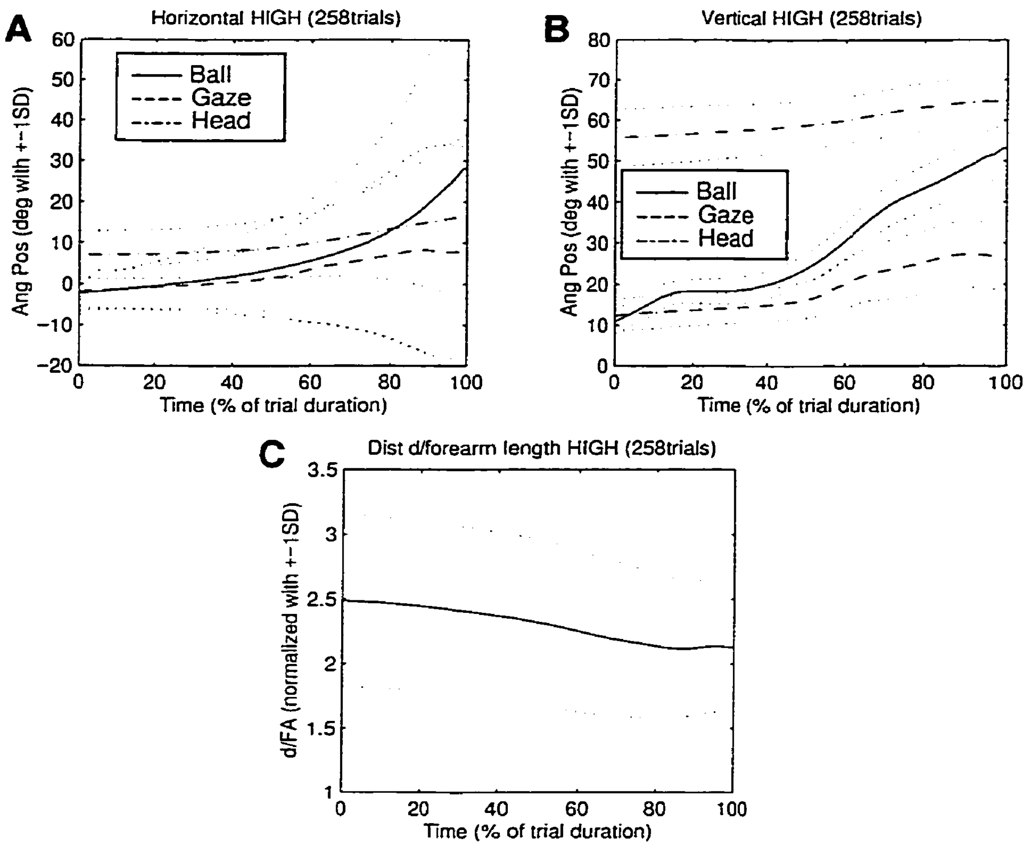

Figure 14. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) of high skill participants.

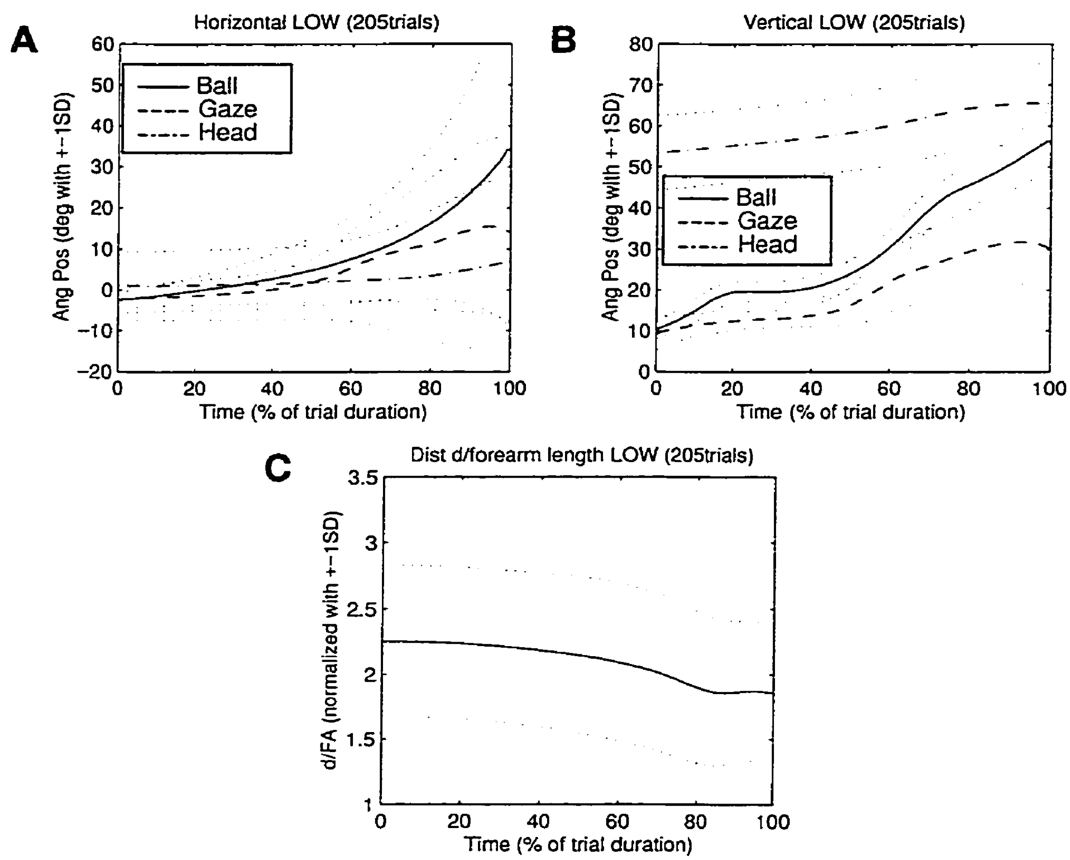

Figure 15. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) of low skill participants.

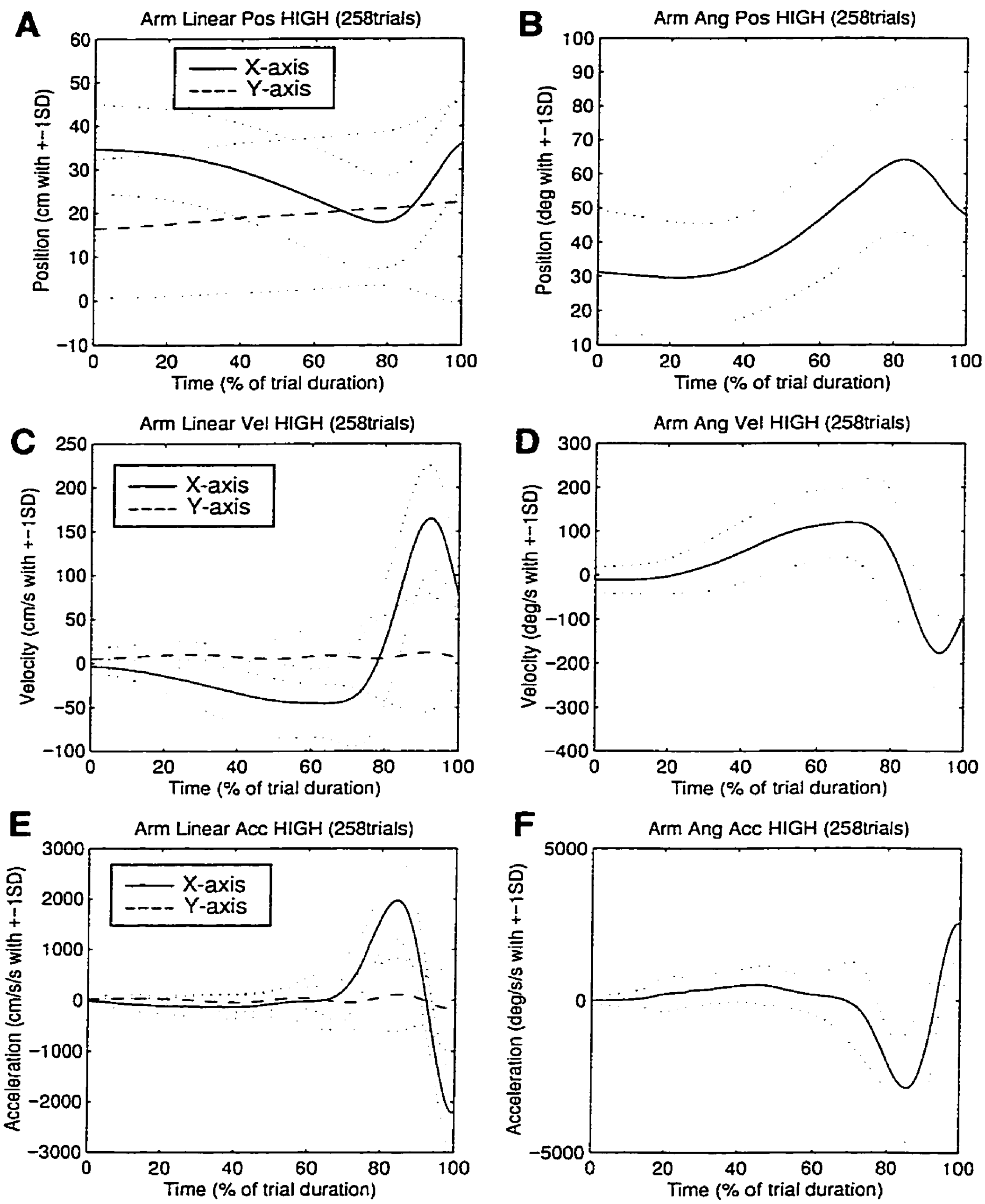

Figure 16. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) of high skill participants.

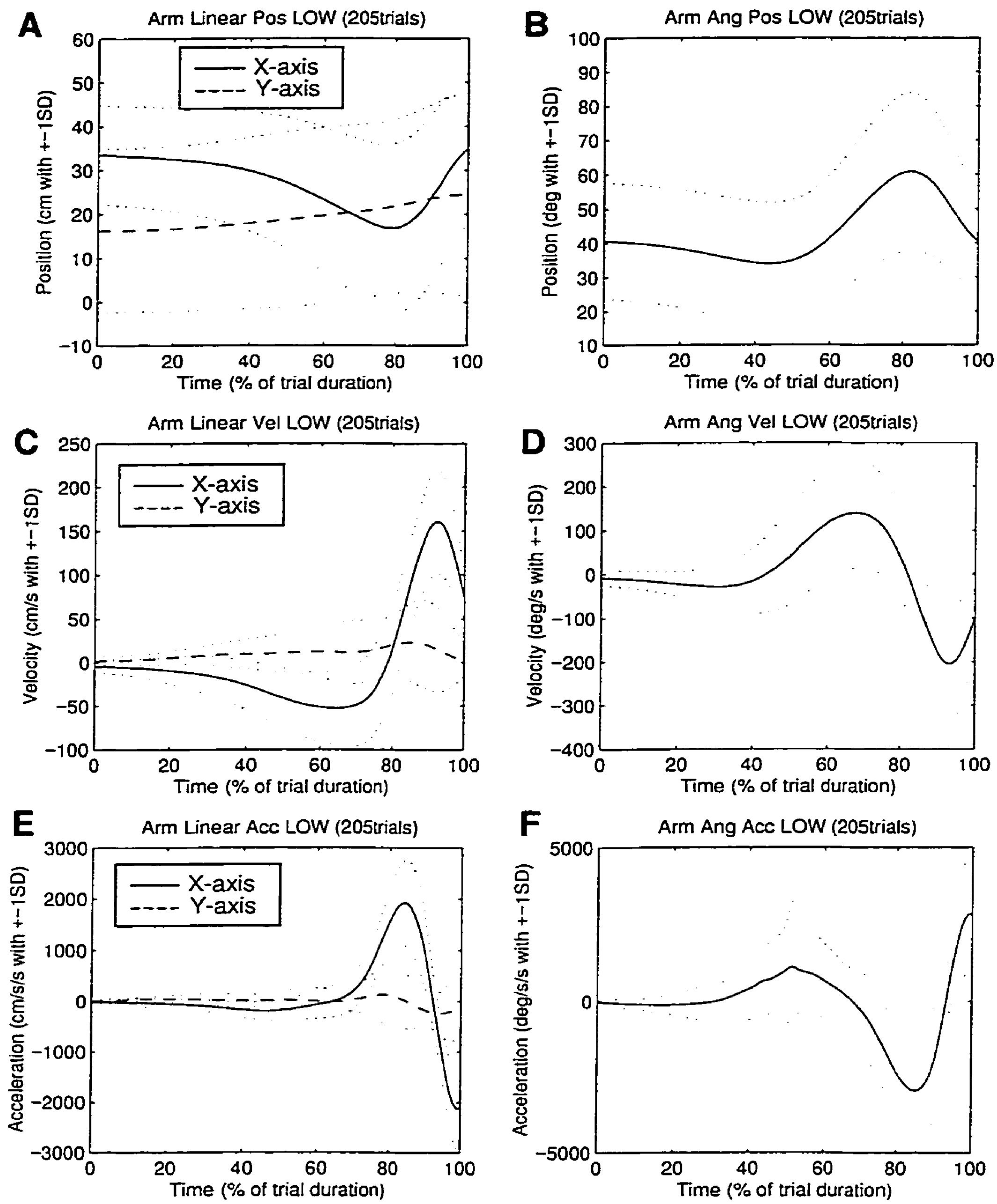

Figure 17. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) of low skill participants.

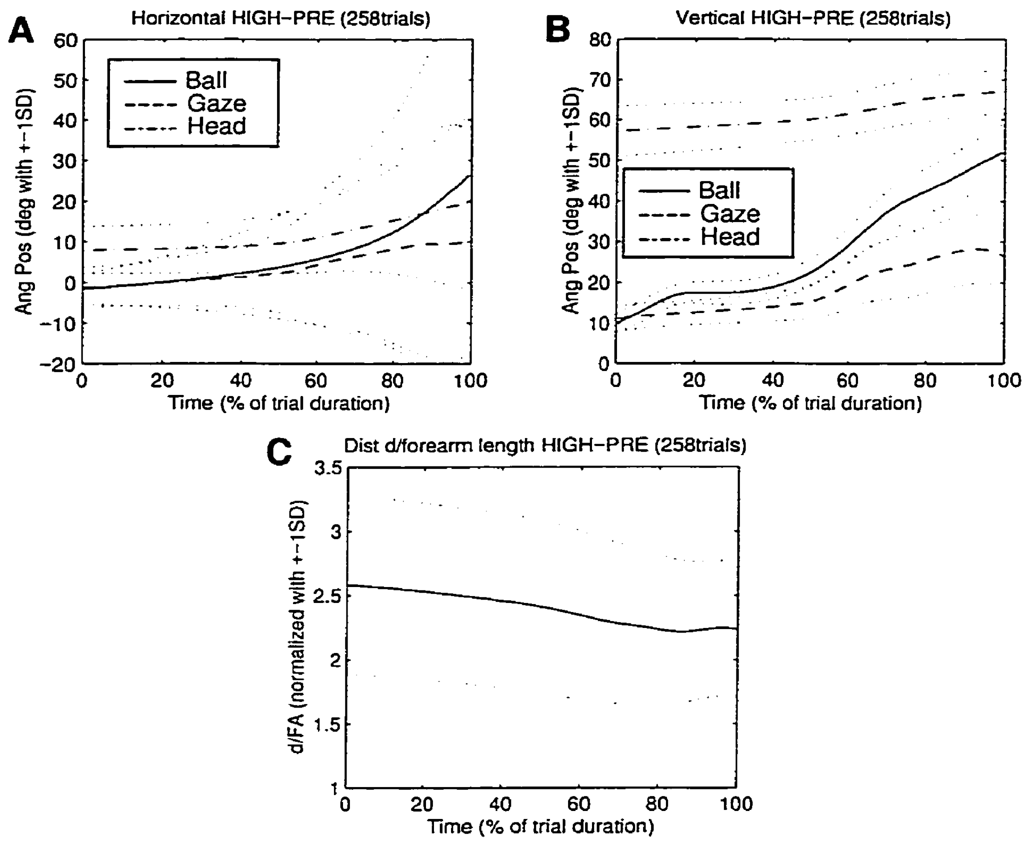

Figure 18. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) of high skill participants in the Pre-cue condition.

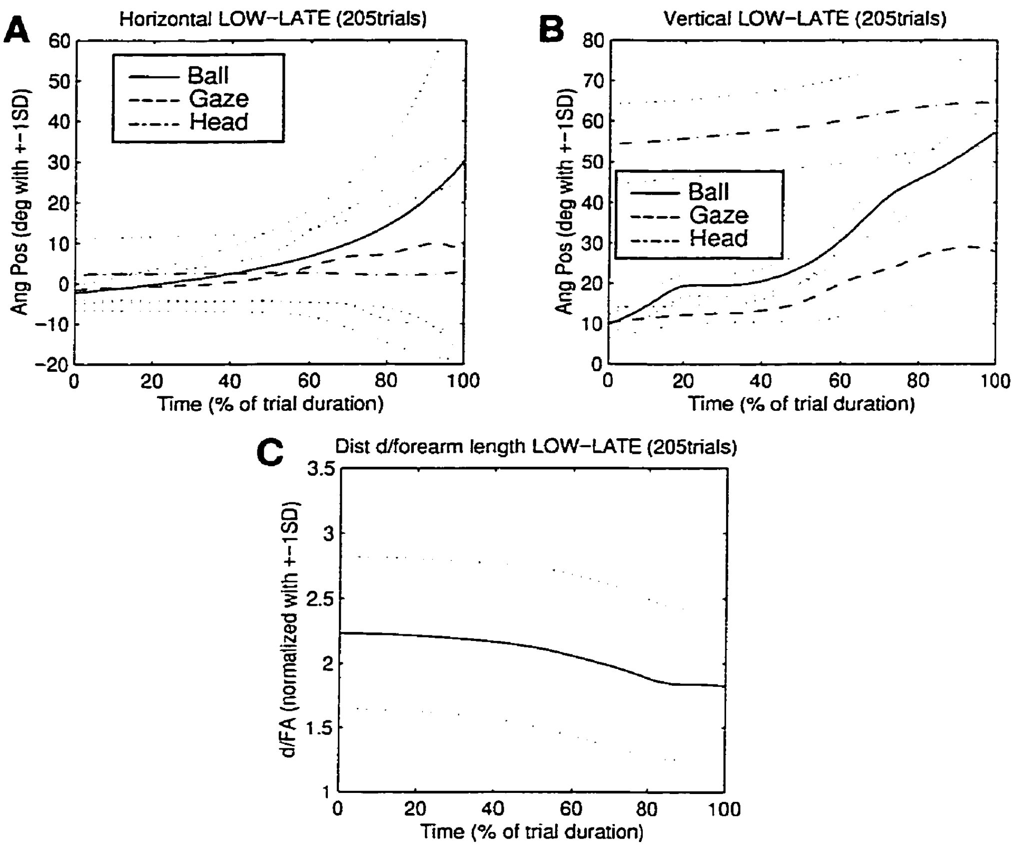

Figure 19. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) of low skill participants in the Late-cue condition.

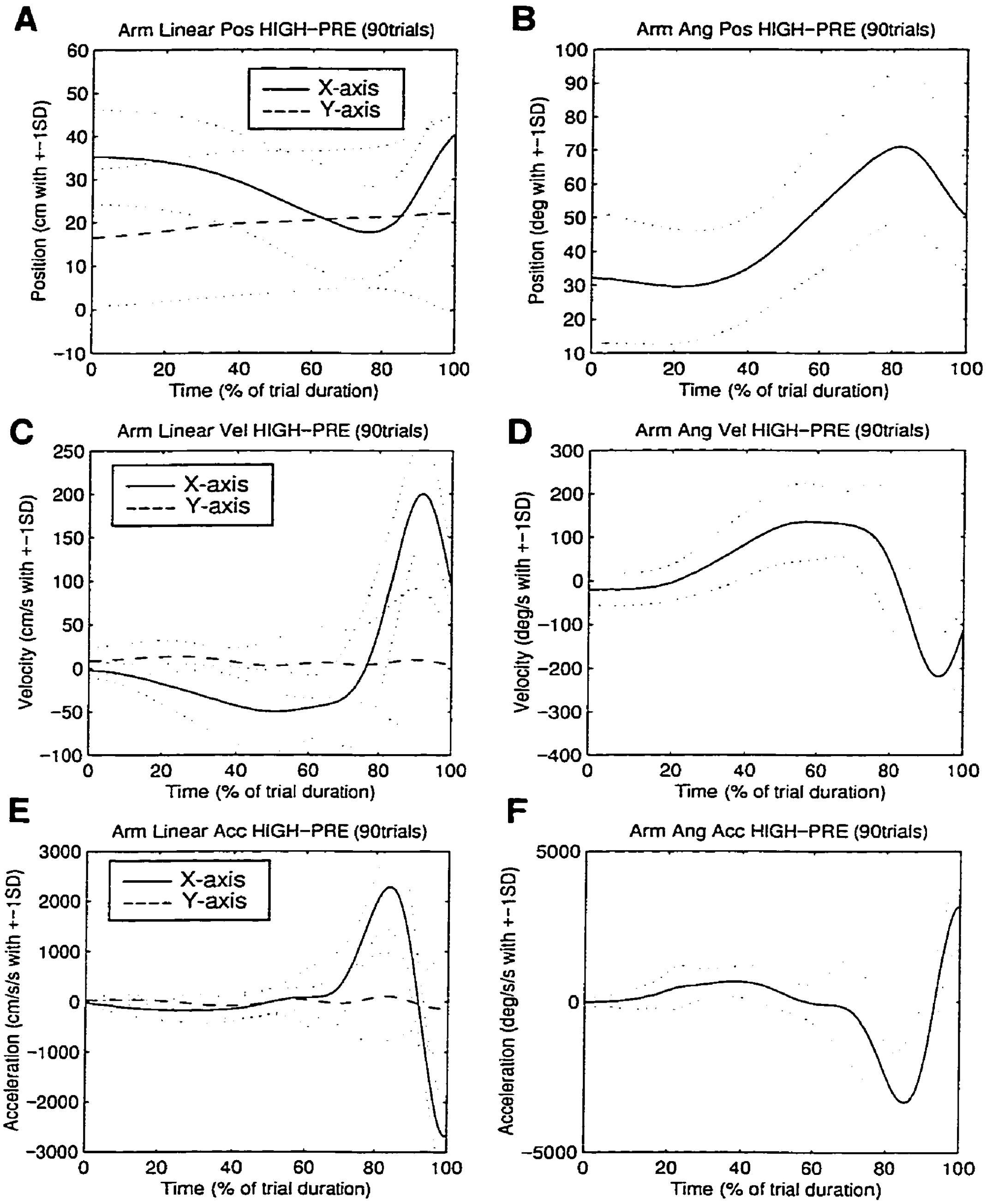

Figure 20. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) of high skill participants in the Pre-cue condition.

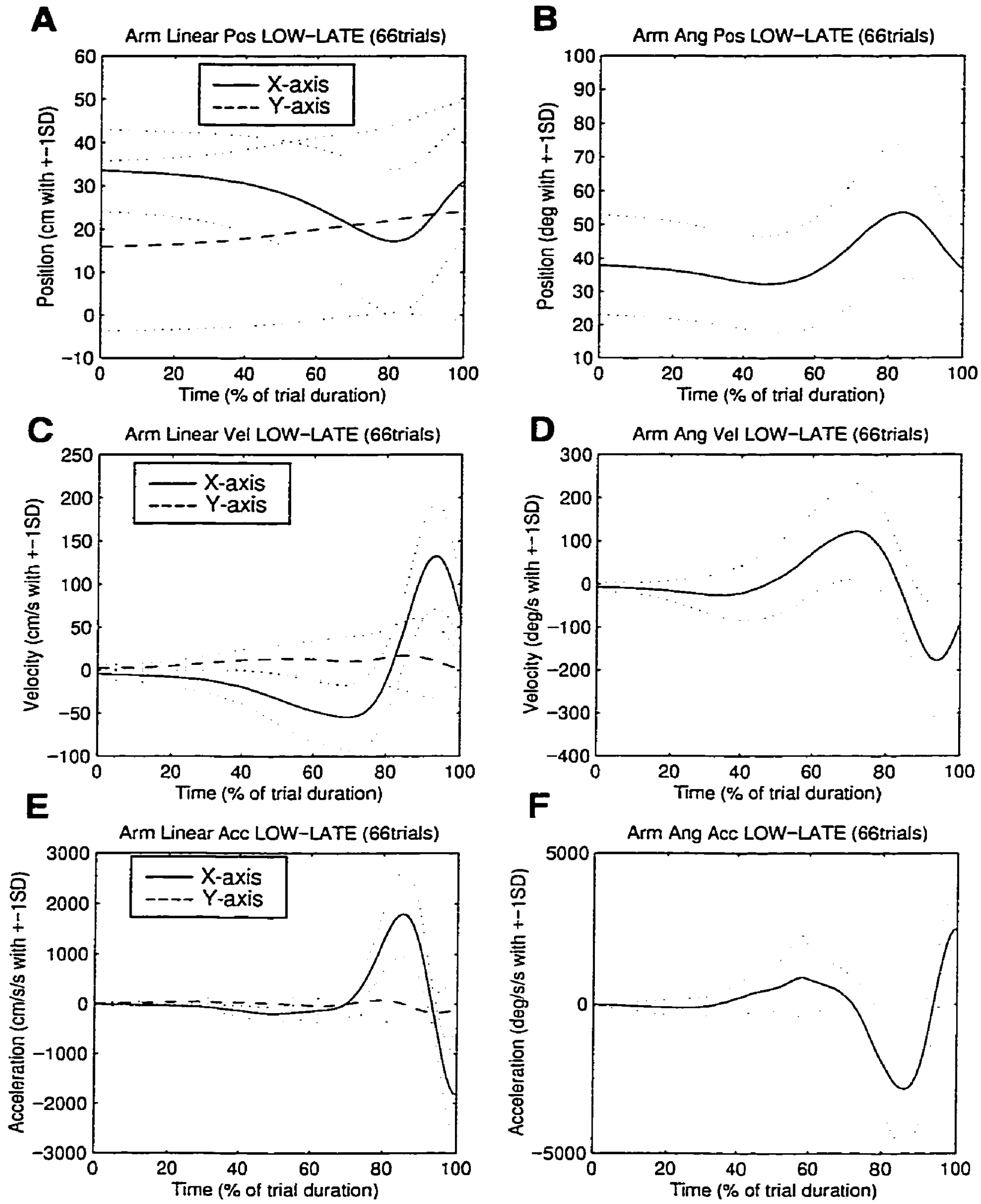

Figure 21. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) of low skill participants in the Late-cue condition.

compared with low skill participants in the Late-cue condition. High skill participants in the Pre-cue condition (Figures 18A and 18B) tracked the ball with gaze longer and moved their head more than low skill participants in the Late-cue condition (Figures 19A and 19B) did. The distance between head position and ball trajectory (distance d) was greater for high skill/Pre-cue combination at the ball-bat contact moment (Figures 18C and 19C). Arm movements of high skill participants performing the task in the Pre-cue condition (Figure 20), when compared to the low skill participants under Late-cue condition (Figure 21), showed the following characteristics: larger movements, with a slightly longer duration of the forward phase, earlier increase in the linear and angular velocity and acceleration during the arm backward phase, and higher linear and angular peak velocity and peak acceleration during the arm forward phase.

Figures 22, 23, 24, and 25 show the behaviour of head, gaze, and arm during hits and misses. Head, gaze, arm movements and the distance d were very similar during hits and misses. The effect of hitting accuracy on the target area was not observable in any of these biomechanical variables.

Plotting and Analysis of Gaze Data

The three-dimensional visual angle between line of gaze and the edge of the ball was determined for each trial during ball flight. Figures 26A, 26C and 26E (left column) show the mean (with standard deviations) for Pre, Early, and Late-cue conditions. The dotted horizontal line indicates three degrees of visual angle, the threshold for QE and TMT. QE and TMT data were derived from each trial curve represented by the mean plots in Figures 26A, 26C, and 26E and entered in the statistical analyses of gaze.

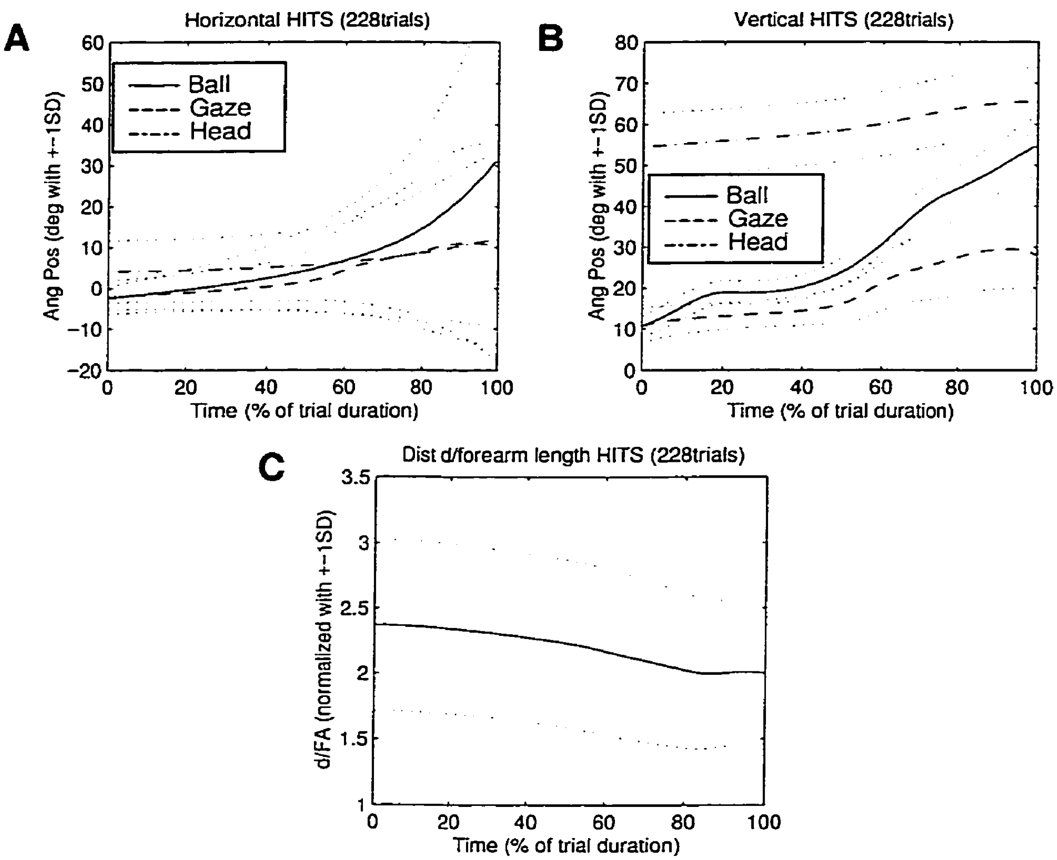

Figure 22. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) during hits.

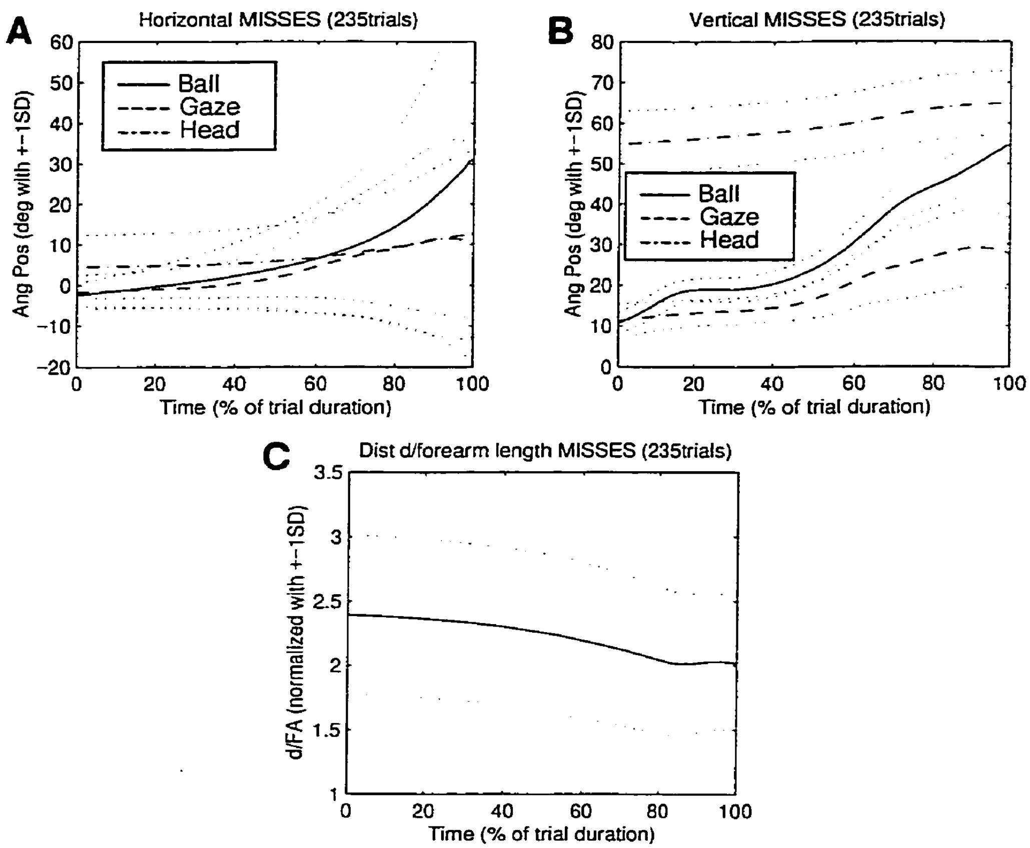

Figure 23. Mean horizontal (A) and vertical (B) movement of the ball (solid), gaze (dash), and head (dash-dot), and the distance between head and ball direction normalized by forearm length (C) as a function of time (% of trial duration) during misses.

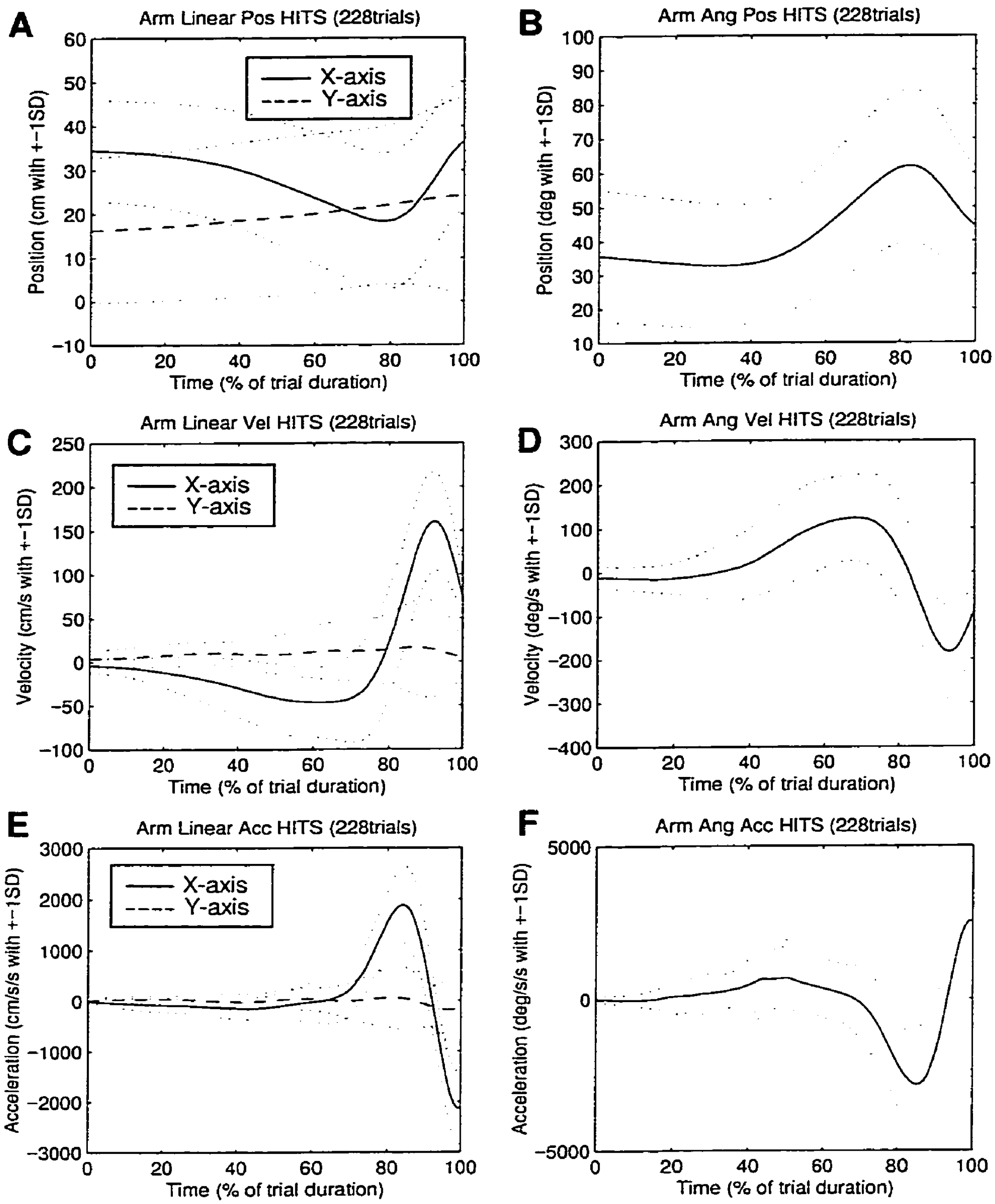

Figure 24. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) during hits.

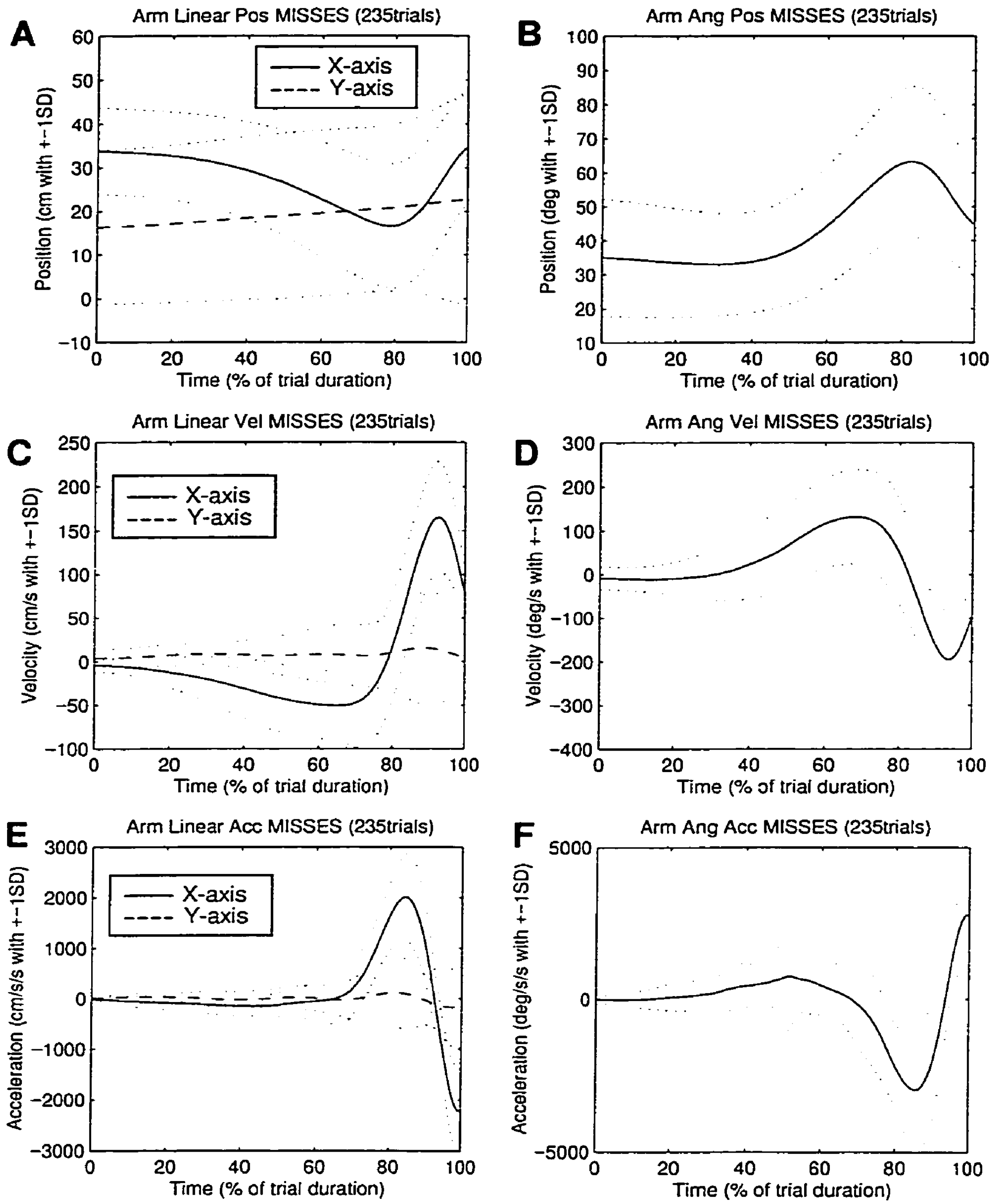

Figure 25. Mean X-axis (solid) and Y-axis (dash) linear position (A), velocity (C), and acceleration (E) and angular position (B), velocity (D), and acceleration (F) of the arm as a function of time (% of trial duration) during misses.

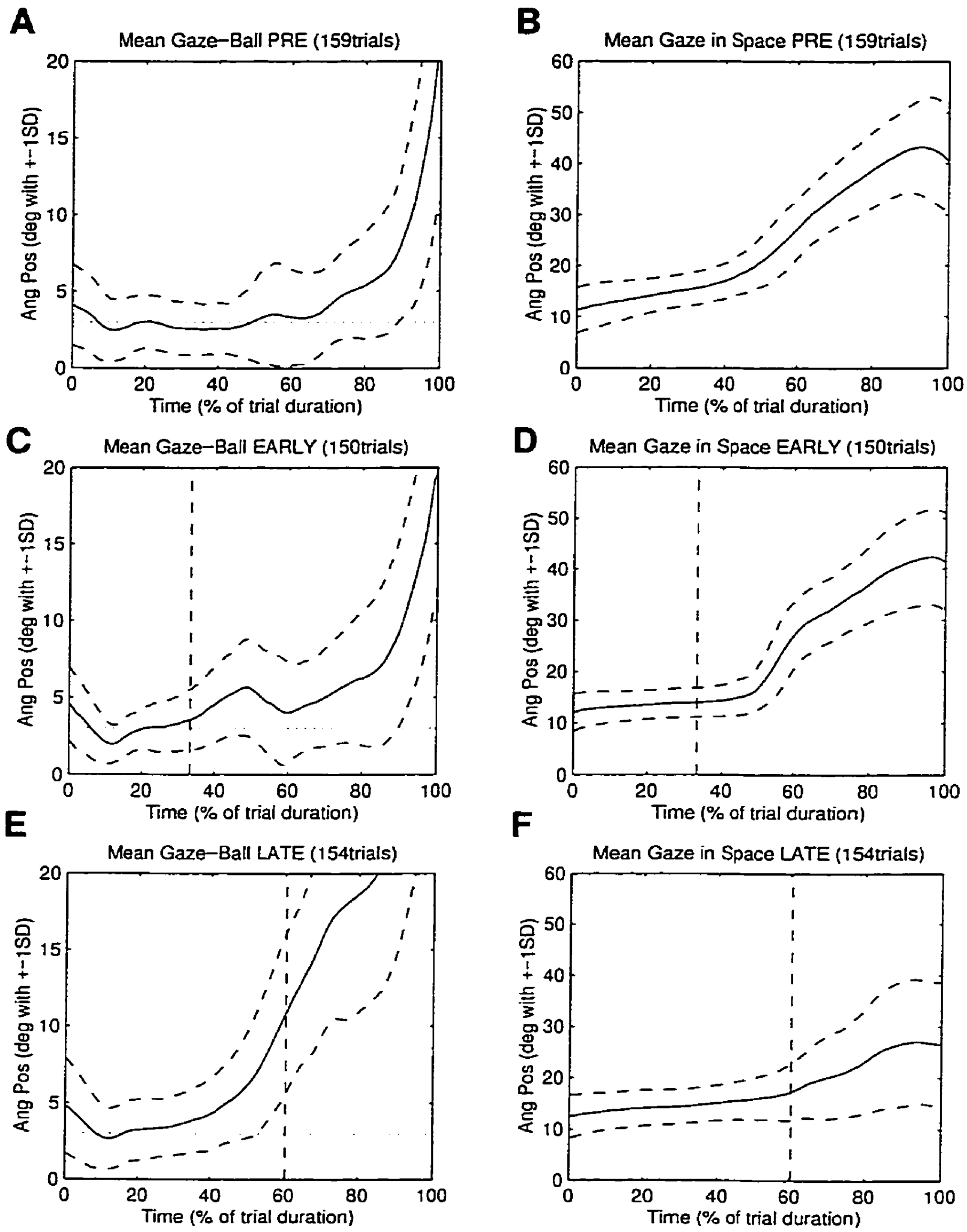

Figure 26. Mean gaze relative to the ball edge 3-D angle (A, C, and E) and gaze in space angle (B, D, and F) as a function of time (percent) for Pre-cue (top), Early-cue (middle), and Late-cue (bottom) conditions. Horizontal dotted lines on gaze-ball plots represent the 3-deg limit for QE. Vertical dashed lines on early-cue and late-cue plots represent cue-on time.

The three-dimensional visual angle between line of gaze and X-axis of the transmitter coordinate system was also determined for each trial during ball flight. Figures 26B, 26D, and 26F (right column) show the mean plots for Pre, Early, and Late-cue conditions. EHS data were derived from each trial curve represented by the mean plots in Figures 26B, 26D, and 26F, and entered in the statistical analyses of gaze.

Missing Data

A review of the data indicated that data were missing for two reasons. In a few trials (17 of 480), a trial was missing due to a participant being unable to make five hits or a technical problem with a computer file. In this case, mean values were used for each participant by cue condition, accuracy, and trial. More interesting was that participants did not use a gaze behaviour (QE, TMT, and EHS) on a significant number of trials. Gaze was missing for this reason in 144 of 480 trials.

On a single trial, four combinations of missing gaze data were observed: QE may occur and EHS be absent; EHS may occur and QE be absent; both QE and EHS may occur; or both may be absent. Table 3 shows the possible combinations in all trials, by Cue Condition and Accuracy for all participants. In Table 3, code 1 refers to Only QE, code 2 was Only EHS, code 3 was both QE and EHS, code 4 was No QE/No EHS, and code 5 represented missing trials. Table 4 summarizes the percentage of occurrence of combinations of QE and EHS during hits and misses of Pre, Early, and Late-cue conditions for each group. Both QE and EHS occurred in 66.7% and 66.2% of the trials of high skill and low skill groups, respectively. Only QE occurred in 16% and 15.3%, Only EHS occurred in 7.7% and 11.6%, and No QE/No EHS occurred in 5.3% and 4.8%

Table 3. Occurrence of QE and EHS by Cue Condition, Accuracy, and Trials for all participants. Codes for gaze occurrences are: Only QE (1), Only EHS (2), QE and EHS (3), No QE/No EHS (4), and Missing Trial, TM (5).

		Pre-cue										Early-cue										Late-cue									
		Hits					Misses					Hits					Misses					Hits					Misses				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	H1	3	3	3	3	3	3	3	3	3	1	5	5	5	5	5	5	5	5	5	5	1	1	1	1	1	3	1	1	1	1
	H2	4	3	1	2	3	3	1	3	3	3	3	2	3	2	3	3	2	3	3	3	1	1	2	4	4	4	4	4	1	4
	H3	3	3	3	3	1	3	3	3	3	1	3	3	3	3	3	3	3	3	3	3	3	3	1	1	3	3	3	3	3	3
	H4	3	3	2	2	3	2	2	3	3	3	3	3	2	3	4	2	3	2	3	3	3	2	2	4	3	2	2	3	2	2
HS	H5	3	3	3	3	3	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	5	5	3	1	3	1	4
	H6	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1	1	4	1	1
	H7	3	3	3	1	3	3	3	3	1	3	3	3	3	3	3	3	3	3	3	3	1	3	4	3	3	3	3	3	2	2
	H8	3	1	1	3	3	3	1	1	3	3	3	3	3	3	3	1	1	3	3	3	3	2	3	3	3	3	3	3	3	3
	H9	3	3	3	3	3	3	3	3	1	3	3	3	3	1	3	3	3	3	3	3	1	1	3	3	3	3	4	3	3	4
	L1	3	3	4	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	3	1	3	3	3	1	1	1	1	1	1
	L2	3	3	3	3	3	3	3	3	3	1	3	3	3	3	3	3	3	3	3	2	1	1	1	1	3	3	3	3	3	1
	L3	3	3	3	3	1	3	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	3	3	3	1	3
LS	L4	3	3	3	3	3	3	3	3	3	3	1	3	3	3	3	2	3	3	3	1	2	3	4	1	5	3	3	3	1	1
	L5	3	3	3	3	5	1	2	3	3	3	2	2	2	3	2	2	3	3	2	3	2	2	3	3	2	2	3	4	2	2
	L6	3	2	3	3	3	3	3	3	3	3	1	3	3	3	3	3	2	3	3	3	4	4	4	1	4	1	1	1	1	3
	L7	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3	2	3	3	3	4	4	5	5	5	1	2	2	4	2

Table 4. Frequency of occurrence of gaze behaviour combinations as a function of cue condition and accuracy for high (HS) and low skill (LS) groups.

Skill Group	Gaze Combination	Pre-cue Hits	Pre-cue Misses	Early-cue Hits	Early-cue Misses	Late-cue Hits	Late-cue Misses
	QE and EHS	13.3	13.0	13.0	13.0	7.0	7.4
HS	Only QE	1.9	3.0	0.4	0.7	5.9	4.1
	Only EHS	1.1	0.7	1.1	1.1	1.5	2.2
	No QE/No EHS	0.4	0	0.4	0	1.5	3.0
	QE and EHS	14.8	14.3	13.3	13.3	4.3	6.2
LS	Only QE	0.5	1.4	1.0	0.5	5.2	6.7
	Only EHS	0.5	1.0	2.4	2.9	1.9	2.9
	No QE/No EHS	0.5	0	0	0	3.3	1.0

of the trials of high skill and low skill groups, respectively. Missing data (code 5 in Table 3) represented 4.4% and 2.4% of the trials of high skill and low skill groups, respectively. Missing gaze durations were set at zero, since in that trial the gaze behaviour was possible but not present. Gaze onsets and offsets were then estimated from available trials, and the analyses run with missing values.

Quiet Eye (QE)

QE onset. A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on QE onset data. Although the main effect skill reached statistical significance, it was embedded in a two-way interaction (Accuracy X Skill), $F(1, 64) = 5.01$, $p = .04$. This indicated that the low skill group had a later QE onset during misses ($M = 24.0\%$, $SD = 22.7$) than hits ($M = 17.7\%$, $SD = 20.9$), whereas the high skill group had similar QE onset for hits ($M = 11.7$, $SD = 18.6$) and misses ($M = 10.0\%$, $SD = 15.5$), as shown in figure 27. Note that a relative time of 0% indicated service ball-bat contact and 100% ball-bat contact by the participant.

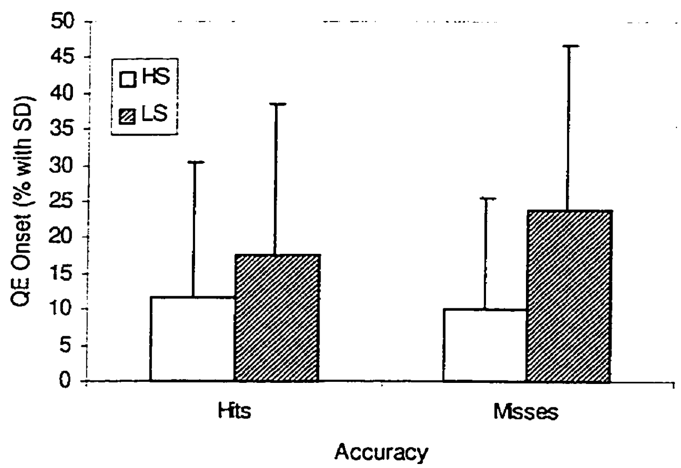

Figure 27. QE onset of high skill (HS) and low skill (LS) groups during hits and misses.

QE onset differed significantly across cue conditions as well, $F(2, 64) = 6.14$, $p = .006$. This significant finding was followed up by three pairwise comparisons of the levels of cue condition. A Bonferroni adjustment of probabilities for multiple comparisons was used and, therefore, each comparison was tested using an alpha level of .0167.They revealed that QE onset differed significantly between Early-cue and Late-cue conditions, $F(1, 25) = 13{,}99$, $p = .002$, although the comparisons between Pre-cue and Early-cue, and between Pre-cue and Late-cue conditions were non-significant. Mean QE onset occurred at 15.1% (SD = 20.2) of the trial duration in the Pre-cue, 21.6% (SD = 23.2) in the Early-cue, and 7.5% (SD = 10.8) in the Late-cue condition. No other main effects or interactions were significant.

QE offset. A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on QE offset data. It revealed that cue condition significantly affected QE offset, $F(2, 64) = 26.91$, $p < .001$. This finding was followed up by examining three pairwise comparisons of the levels of cue condition. A Bonferroni adjustment of probabilities for multiple comparisons was used and each comparison was tested at an alpha level of .0167. These tests found that all three pairwise comparisons were significant: Pre and Early-cue, $F(1, 38) = 12.81$, $p = .003$, Early and Late-cue, $F(1, 25) = 16.88$, $p = .001$, and Pre and Late-cue, $F(1, 24) = 55.05$, $p < .001$. QE terminated earlier in the trial as the cue was more delayed, occurring at 70.6% (SD = 19.5), 59.6% (SD = 26.6), and 38.0% (SD = 13.3), respectively, for Pre, Early, and Late conditions as shown in Figure 28. No other main effects or interactions were significant.

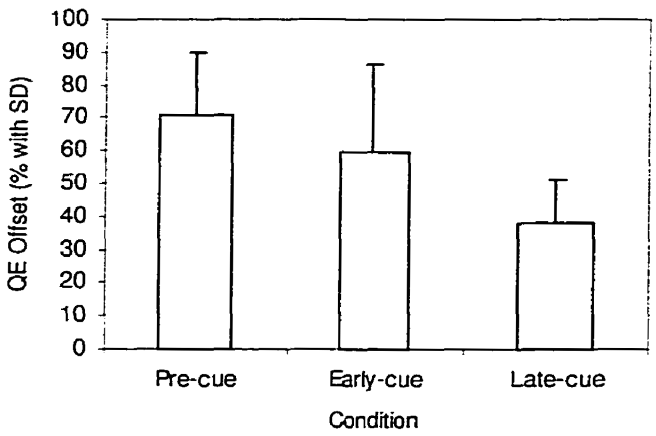

Figure 28. QE offset in the Pre-cue (PR), Early-cue (EA), and Late-cue (LA).

QE duration. A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on the QE duration data. It revealed that the duration of QE varied significantly with cue condition, $F(2, 112) = 42.09$, $p < .0001$. Three pairwise comparisons of the levels of cue condition were examined to follow up this finding. A Bonferroni adjustment for multiple comparisons was made with each comparison using an alpha level of .0167. These tests found that all three pairwise comparisons were significant: Pre and Early-cue, $F(1, 56) = 37.27$, $p < .0001$, Early and Late-cue, $F(1, 56) = 23.13$, $p < .0001$, and Pre and Late-cue, $F(1, 56) = 51.94$, $p < .0001$. QE occurred in average during 51.9% ($SD = 26.5$) of the trial in the Pre-cue condition, 33.4% ($SD = 21.5$) in the Early-cue, and 22.3% ($SD = 16.7$) in the Late-cue, as shown in Figure 29. No other main effects or interactions were significant.

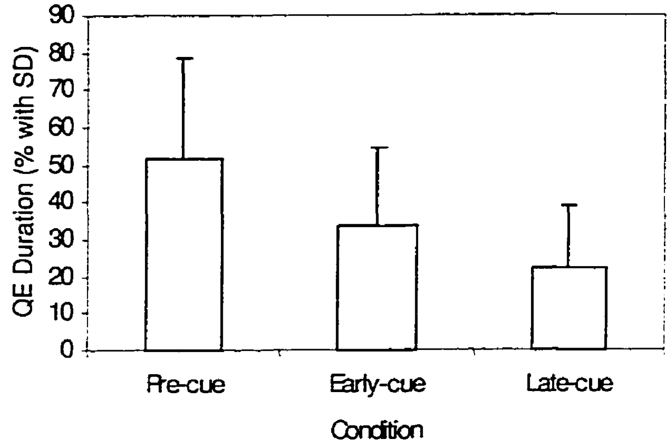

Figure 29. QE duration in the Pre-cue (PR), Early-cue (EA), and Late-cue (LA) conditions.

Tracking During Movement Time (TMT)

TMT occurred in 16 out of 463 trials analyzed and therefore these data were not subject to statistical analyses.

Eye-Head Stabilization (EHS)

EHS Onset. A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on EHS onset data. It revealed a significant main effect for trials, $F(4, 45) = 3.61$, $p = .01$. Mean EHS onset was lowest in trial 1 ($M = 81.5\%$, $SD = 9.1$) whereas it was similar across other trials. Means for trials 1 through 4 were 84.8, 83.7, 84.4, and 83.7 % (SDs = 6.7, 8.0, 7.4, and 7.5, respectively). No other main effects or interactions were significant.

EHS Offset. A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on EHS offset data. Although a two-way (Cue Condition X Skill) and a three-way (Cue Condition

X Accuracy X Skill) interactions reached significance, Fs = 3.78 and 4.24, ps = .04 and .03, respectively, they did not reveal a clear pattern in the data. The lowest mean EHS offsets occurred in the misses of high skill participants during the Pre-cue condition (M = 92.6%, SD = 8.3) and in the misses of low skill participants during the Late-cue condition (M = 92.2%, SD = 8.8). All other marginal means for combinations among levels of cue condition, accuracy and skill were similar and in the range 95.3 to 98.6%. No other significant main effects or interactions were significant.

EHS duration. A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on EHS duration data. Although the interaction of Trials by Skill was significant, $F(4, 112) = 3.51$, $p = .032$, there was not a consistent pattern across trials for either group. Mean EHS duration in trial 1was highest for the high skill group (13.2%, SD = 9.6) and lowest for the low skill group (8.3%, SD = 5.9). Mean EHS duration for trials 2 through 5 for the high and low skill groups were similar, ranging from 9.0 to 9.6% and from 8.7 to 10.6%, respectively. The main effect of cue condition was non-significant, but it was approaching significance, $F(2, 112) = 3.34$, $p = .05$. Mean EHS duration was 10.1% (SD = 5.3) in the Pre-cue, 11.3% (SD = 5.4) in the Early-cue, and 7.9% (SD = 10.4) in the Late-cue condition. No other main effects or interactions were significant.

Plotting and Analysis of Arm Data

Mean arm angular position and arm angular velocity are shown in Figure 30. The measure of arm angular position was used to determine MT onset. The measure of arm angular velocity provided AVC values, which were entered into the statistical analyses.

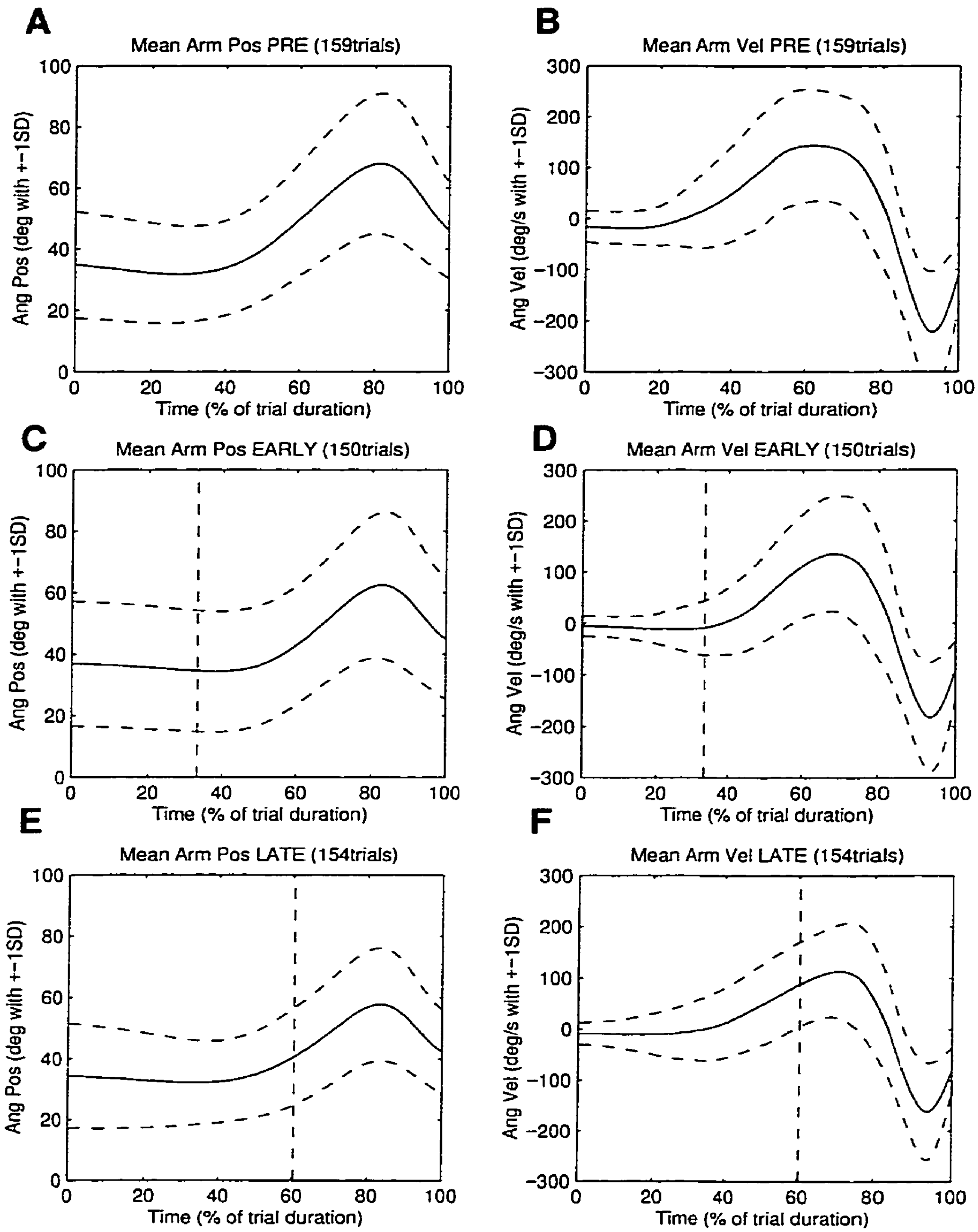

Figure 30. Mean arm angular position (A, C, and E) and arm angular velocity (B, D, and F) as a function of time (% of trial duration) for Pre-cue (top), Early-cue (middle), and Late-cue (bottom) conditions. Vertical dashed lines on Early-cue and Late-cue plots represent cue-on time.

Movement Time (MT)

Relative MT (percent). A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on MT (percent) onset data. The same analysis was used on MT (percent) duration data. These analyses showed that relative MT onset and duration (percent) were not affected significantly by cueing, skill level or accuracy. No main effects or interactions were significant. Note that all overall relative MT offsets were 100% and, therefore, they were not subjected to statistical analyses. The mean relative MT onset was 80.1% (SD = 6.0) and the mean relative MT duration was 19.9% (SD = 6.0).

Absolute MT (milliseconds). A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on MT onset (ms) data. Although the three-way (Cue Condition X Accuracy X Trials) and four-way (Cue Condition X Accuracy X Trials X Skill) interactions reached significance, Fs = 2.15 and 2.54, ps = .04 and .01, respectively, they did not reveal a systematic pattern of differences. However, the analysis clearly revealed that the absolute MT onset (ms) occurred significantly later as the cue was delayed, $F(2, 112) = 21.52$, $p < .001$. This finding was followed up by examining three pairwise comparisons of the levels of cue condition. A Bonferroni adjustment of probabilities for multiple comparisons was used and, therefore, each comparison was tested using an alpha level of .0167. These tests found that all three pairwise comparisons were significant: Pre and Early-cue, $F(1, 56) = 7.44$, $p = .016$, Early and Late-cue, $F(1, 56) = 33.65$, $p < .001$, and Pre and Late-cue, $F(1, 56) = 20.58$, $p < .001$. Absolute mean MT onset was 605.2 ms (SD = 60.9) in the Pre-cue, 628.9 ms (SD = 63.9) in the Early-cue, and 664.8 ms (SD = 70.9) in the Late-cue, as shown in Figure 31. No other main effects or interactions were significant.

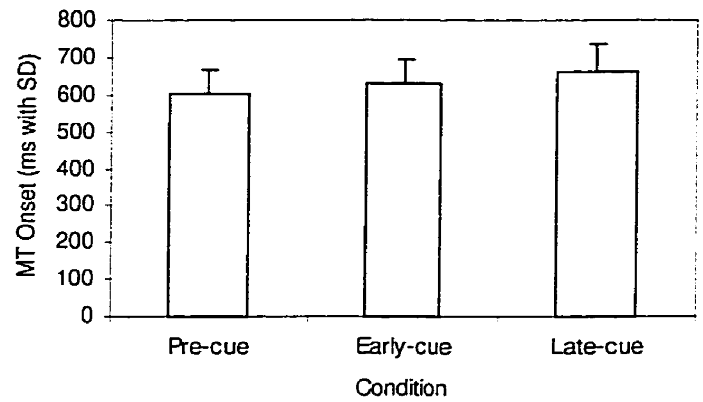

Figure 31. MT onset (ms) in the Pre-cue, Early-cue, and Late-cue conditions.

A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on absolute MT duration (ms) data. No significant main effects or interactions were found. Mean absolute MT duration (ms) was 157.6 ms (SD = 49.9). The same type of analysis was used on absolute MT offset (ms) data. Note that MT offset (ms) is the same as ball flight time, and that two significant three-way interactions for ball flight time (Cue Condition X Trials X Skill and Cue Condition X Accuracy X Trials) were reported earlier. This analysis also revealed, similarly to MT onset (ms) results, that absolute MT offset (ms) was significantly affected by cue condition, $F(2, 112) = 15.77$, $p < .001$. Three pairwise comparisons were examined and a Bonferroni adjustment of probabilities for multiple comparisons used with each comparison tested at an alpha level of .0167. These tests found that absolute MT offset differed significantly between Pre and Late-cue, $F(1, 56)$

=24.40, p < .001, and between Early and Late-cue, F(1, 56) = 12.74, p = .003, although the difference between Pre and Early-cue was not significant. MT offset was 766.4 ms (SD = 53.5) in the Pre-cue condition, 784.1 ms (SD = 62.3) in the Early-cue condition, and 818.5 (SD = 63.2) in the Late-cue condition, as shown in Figure 32. No other main effects or interactions were significant.

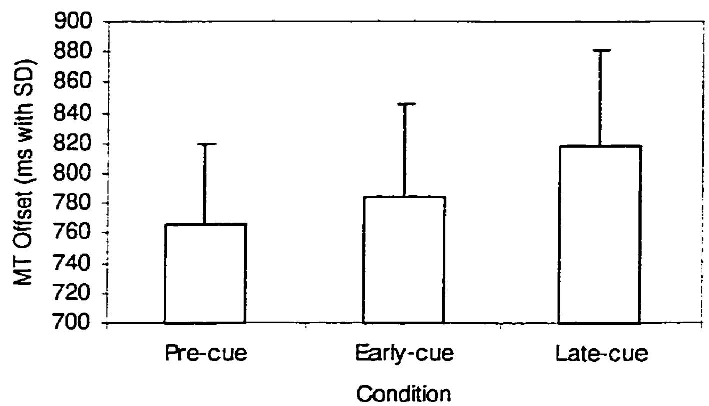

Figure 32. MT offset (ms) in the Pre-cue, Early-cue, and Late-cue conditions.

Arm Velocity at Contact (AVC)

A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on AVC data. It revealed that AVC was significantly reduced by cueing, F (2, 112) = 7.60, p = .002. Three pairwise comparisons across the three cue conditions were examined to follow up this finding. A Bonferroni adjustment for multiple comparisons was made and an alpha level of .0167 used for each comparison. These tests found two significant pairwise comparisons: between Pre and Early-cue, F(1, 56) = 10.53, p = .006, and between Pre and Late-cue, F(1, 56) = 10.36, p = .006. However the comparison between Early and Late-cue was non-significant, $F(1, 56) = 1.28$, $p = .28$. Mean AVC was -110.8 deg/s (SD = 61.6) in the Pre-cue, -89.2 deg/s (SD = 53.9) in the Early-cue, and -81.1 deg/s (SD = 45.4) in the Late-cue condition, as shown in Figure 33. A main effect for accuracy was also found, $F(1, 112) = 10.42$, $p = .006$. Figure 34 shows that the mean AVC during misses (M = -97.3 deg/s, SD = 58.2) was significantly higher than during hits (M = -90.1 deg/s, SD = 52.3). No other main effects or interactions were significant.

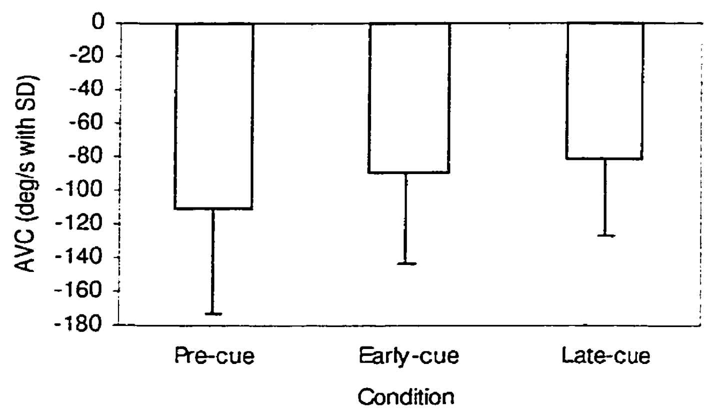

Figure 33. AVC during Pre-cue, Early-cue, and Late-cue conditions.

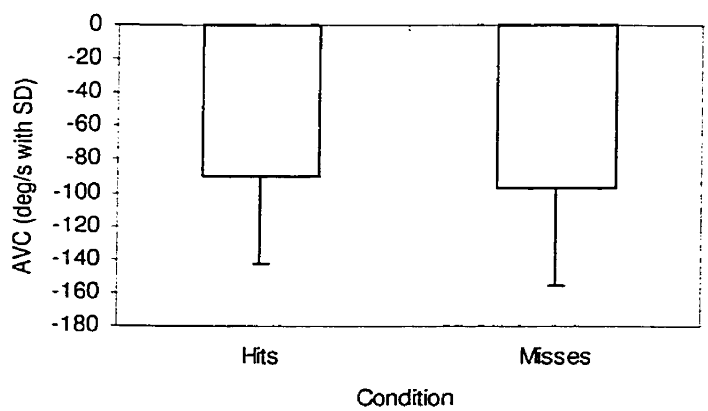

Figure 34. AVC during hits and misses.

Post-Hoc Analyses

In an effort to understand more about the head and gaze behaviours during Pre, Early and Late-cue conditions, three variables were identified a posteriori: gaze relative to the cue (GC), horizontal head movement (Hh), and horizontal gaze movement (Gh). GC indicated the extent to which participants allowed their gaze to deviate from the cue lights. GC was defined as the three-dimensional angular distance between line-of-gaze and the cue position at cue onset time. Hh and Gh indicated how head and gaze moved towards the ball in the horizontal plane, which provided a more clear measure of location on the table where head and gaze stopped to follow the ball. Hh was defined as the maximum angular distance between the head vector and X-axis of the transmitter coordinate system on the horizontal plane. Gh was defined as the maximum angular distance between the line-of-gaze and X-axis of the transmitter coordinate system on the horizontal plane.

Gaze relative to the cue (GC). A skill (2) by cue condition (2) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on GC data. Note that GC was determined only for Early and Late-cue conditions because it could not be determined during the Pre-cue condition as the target was cued prior to the onset of the trial and recording of gaze data. This analysis revealed that gaze was significantly closer to the cue light when the cue was activated in the Early-cue condition ($M = 5.3$ deg, $SD = 3.0$) than in the Late-cue condition ($M = 7.6$, $SD = 5.3$), $F(1, 56) = 7.5$, $p = .016$.

Horizontal Head Movement (Hh). A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on Hh data. It revealed that Hh was significantly affected by cue condition, $F(1, 112) = 16.05$, $p < .001$. Three pairwise comparisons of the levels of cue condition were examined to follow up this finding. A Bonferroni adjustment for multiple comparisons was made and an alpha level of .0167 used for each comparison. These tests found two significant pairwise comparisons: between Pre and Late-cue, $F(1, 56) = 23.67$, $p < .001$, and between Early and Late-cue, $F(1, 56) = 18.40$, $p = .001$. However, the comparison between the Pre and Early-cue conditions was non-significant. Mean Hh was 17.1 deg ($SD = 14.4$) in the Pre-cue, 17.7 deg ($SD = 18.2$) in the Early-cue, and 5.3 deg ($SD = 11.5$) in the Late-cue condition, as shown in Figure 35. No other main effects or interactions were significant.

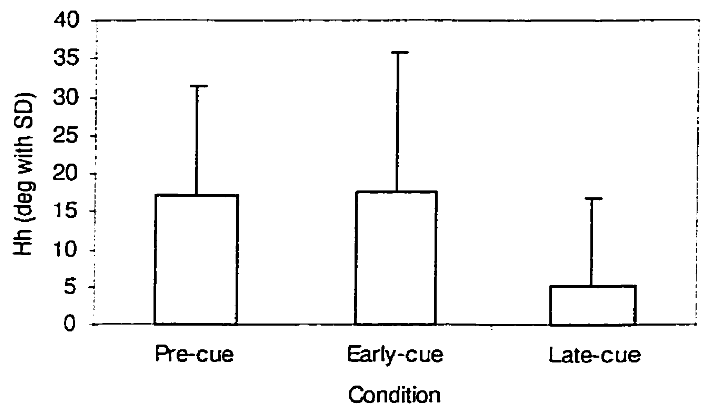

Figure 35. Hh during Pre-cue, Early-cue, and Late-cue conditions.

Horizontal Gaze Movement (Gh). A skill (2) by cue condition (3) by accuracy (2) by trials (5) mixed design ANOVA with repeated measures on the last three factors was conducted on Gh data. It revealed that Gh was significantly affected by cue condition, $F(1, 112) = 50.96$, $p < .001$. This finding was examined using three pairwise comparisons over the three cue conditions. A Bonferroni adjustment for multiple comparisons was used and an alpha level of .0167 adopted for each comparison. Similarly to Hh results, these tests showed two significant pairwise comparisons: between Pre and Late-cue, $F(1, 56) = 58.06$, $p < .001$, and between Early and Late-cue, $F(1, 56) = 72.30$, $p < .001$. The comparison between Pre and Early-cue conditions was non-significant. Mean Gh was 31.0 deg (SD = 8.9) in the Pre–cue, 28.6 deg (SD = 9.2) in the Early-cue, and 14.7 deg (SD = 9.7) in the Late-cue condition, as shown in Figure 36. No other main effects or interactions were significant.

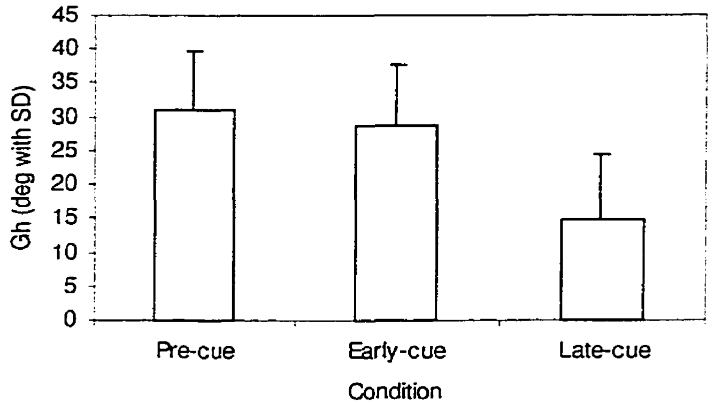

Figure 36. Gh during Pre-cue, Early-cue, and Late-cue conditions.

Participant with Functional Monocularity

All results presented above for the low skill group included data of a participant with functional monocularity (FM). This participant had visual acuity 20/200 in the right eye and was maintained in the present study to provide possible information on the relation between her visual characteristics and performance of the task. Results of this participant were compared to the mean of low skill participants to determine if this was an extreme case in terms of gaze and arm data. Table 5 presents this comparison for the variables percent of hits, onset, offset, and duration of QE, EHS, and MT, and AVC. Despite this participant's poor visual acuity in the right eye, her mean results were compatible with the average for the group. Her ability to hit on the target (percent of hits) in all conditions, her manner of acquiring visual information (QE and EHS) and control arm movements (MT AVC) did not seem to differ with respect to the mean performance and visuo-motor behaviour presented by the low skill group.

Table 5. Comparison between the participant with functional monocularity (FM) and the Low Skill group for percent of hits, QE, EHS, MT, and AVC.

	Participant with FM	Low Skill Group		
	Mean	Mean	Minimum	Maximum
Hits - Without Helmet (%)	30.0	32.9	21.7	45.5
Hits - Pre-cue (%)	42.9	37.6	13.7	50.0
Hits - Early-cue (%)	47.1	35.8	15.0	50.0
Hits - Late-cue (%)	22.2	19.7	8.1	41.7
QE Onset (%)	24.0	20.9	0	77.5
QE Offset (%)	60.8	64.9	12.8	100.0
QE Duration (%)	36.7	44.0	11.4	100.0
EHS Onset (%)	86.5	84.7	52.3	94.0
EHS Offset (%)	96.9	96.6	66.7	100.0
EHS Duration (%)	6.9	9.3	0	43.0
MT Onset (%)	74.7	79.6	56.9	93.1
MT Duration (%)	25.3	20.4	6.9	43.1
AVC (deg/s)	33.8	98.8	10.5	325.5

Discussion

The purpose of this study was to determine how the acquisition of visual information through movement of eyes and head affected the execution of a complex motor skill. The study was realized within the context of the table tennis forehand stroke and three gaze behaviours, QE (Vickers, 1996a) in the preparation phase, or prior to the initiation of forward arm movement, EHS (Ripoll & Fleurance, 1988), and TMT during the execution phase, or movement time. Given the precedents in the literature, participants were expected to track the ball in the initial part of its flight (QE) and then keep the gaze stable on a location in advance of the ball (EHS) as the ball was contacted. Tracking to contact was not expected as found in previous studies by Bahill and LaRitz (1984), Ripoll and Fleurance (1988), and Vickers and Adolphe (1997). Levels of constraint were hitting to right and left targets in three cue conditions (Pre-cue, Early-cue, and Late-cue).

The results support findings in previous studies that have shown that participants keep their eyes on the ball during initial ball flight, or during the QE period (Bahill & LaRitz, 1984; Hubbard & Seng, 1954; Ripoll & Fleurance, 1988; Vickers & Adolphe, 1997) and not during late flight, or TMT. The results also support studies that have demonstrated that participants maintain a stable gaze on a location prior to contact of the ball or EHS (Ripoll, Bard & Paillard, 1986; Ripoll & Fleurance, 1988). In addition, a number of new findings were found that together increase our understanding of the effects of skill level, accuracy and time constraints on visuo-motor coordination. This section initially discuss one case of functional monocularity and the biomechanical analysis of gaze and arm movements. This is followed by the effects of skill level, accuracy and cue condition. Finally, the functions of QE and EHS are focused.

Participant with Functional Monocularity

The case of one participant with poor visual acuity (20/200) in the right eye was used to illustrate possible effects of a functional monocularity on visual and motor behaviour. The comparison between this participant's means and group means showed that functional monocularity did not affect gaze and arm patterns in the present study. Any conclusions derived from this finding should be done with caution. The following aspects limit the generalization of this result: 1) this participant was at beginner level with low experience in table tennis; 2) the absence of effect of monocularity is valid only for the dependent variables measured in this study; and 3) there was only one participant in this situation.

Bootsma and van Wieringen (1988) have found differences in arm velocity and other adaptations when comparing elite table tennis players arm movement patterns under binocular and monocular conditions. However, it is interesting to note that the case in the present study was considerably distinct with regard to the low skill level and the natural rather than laboratory-generated monocular vision.

Biomechanical Analysis

To hit the ball to the cued target area participants first kept gaze close to the ball in the initial part of ball flight and then aligned gaze and head on the area of ball-bat contact around the moment arm was moving forward to hit the ball. When participants knew a priori which target area to respond to, in the Pre-cue condition, gaze and head tracked the ball motion smoothly up to a moment that they stabilized, causing a considerable increase in the distance between gaze and ball in the end of ball flight. When participants had to detect the cue light during ball flight, the movement pattern of gaze and head was altered. In the Early-cue situation, participants did not move gaze and head considerably until the light presentation had occurred, and then moved fast towards the ball to compensate this delay. In the Late-cue condition, the extreme delay in cue presentation did not let participants to track the ball as they attempted in other cue conditions. Small gaze movement with an increased variation occurred in the final 20-30% of the trial duration. The average gaze behaviour in the plots showed that gaze never leaded the ball in both horizontal and vertical dimensions, rather gaze followed the ball movement as much as the time available in the respective cue condition allowed.

In sum, the effect of cueing on gaze and head movements was observable in two aspects. There was decrease in both the duration that gaze was maintained close to the ball in the initial part of the ball flight and the duration that gaze and head were stabilized in the final part of ball flight as the cue light was more and more delayed. The angular distance between the light that came on and the ball over time was not directly assessed. This limited the understanding on how peripheral the visual stimulus was with respect to the ball and its consequences to the strategies chosen by participants to accomplish the task. Future research should adopt such measure.

The task requirement of obtaining visual information of the cued target area later and later in ball flight was also related to changes in arm mechanics. To detect the visual cue, organize and perform the hitting action in shorter intervals, participants adapted themselves by reducing the amplitude of arm movement, the magnitude of peak velocity and peak acceleration, and the distance between head and ball trajectory. This adaptation seemed sufficient to maintain Pre-cue levels of accuracy on the target in the Early-cue condition. However this was not true for the Late-cue condition. The reduction in amplitude, velocity, acceleration of arm action and the distance d also occurred in the Late-cue condition but the levels of accuracy were the lowest.

The comparison between high skill participants performing at Pre-cue condition and low skill participants performing at Late-cue condition confirmed the cue condition effects described above, characterizing even more extreme differences. To solve the problem of hitting the ball to the target area under the most difficult constraints (i.e., latest cue light presentation, largest angular distance between cue light and ball) low skill participants in the Late-cue condition drastically reduced their action patterns of gaze, head, and arm. Note that this adaptation in the visual information acquisition system (gaze and head movements) seemed coupled with the adaptation in the action system (arm movements) as an attempt to overcome the harder cue conditions.

An interesting finding was the total absence of observable differences between the plots describing hits and misses. It was surprising that the variables utilized in this biomechanical analysis were not able to capture differences to characterize distinctively hits and misses. Note that the variables used in this analysis were innovative as gaze and motor behaviour during such a complex sport-related task had their kinematics quantitatively described in a natural environment for the first time. These variables were expected to shed light into the discussion about the causes of an accurate response versus an inaccurate one. The following topics discuss the effects of skill level, accuracy, and cue condition based on statistical analyses.

Effects of Skill Level and Accuracy

The present findings only partially support the hypothesis of significant differences between high and low skill groups for QE. Although the groups clearly differed in their overall ability to produce accurate responses to the target areas (52.9% for the high skill group vs. 31.5% for the low skill group; see Table 2), skill level and accuracy did not significantly affect QE and EHS duration. Mean relative duration of QE for the high skill group was 34% of total flight time and 36% for the low skill group. The interaction of Accuracy X Skill for QE onset was significant. During misses, the low skill group QE onset was delayed (Figure 27). The high skill group, on the other hand, had similar QE onsets for misses and hits. Vickers and Adolphe (1997) showed that an earlier onset of tracking on the ball in the volleyball serve reception was a characteristic of higher skilled participants. These findings indicated the importance of early initiation of tracking. For the low skill group, a delayed initiation provided less than optimal acquisition of crucial visual information for those less experienced in planning and executing table tennis tasks.

Vickers (1996a) also found a significant Accuracy X Skill interaction for QE duration in basketball free throws. Mean QE duration of the expert group was higher during hits (972 ms) than misses (806 ms), whereas near-experts had lower QE duration during hits (357 ms) than misses (393 ms). Also, EHS and only-head stabilization were affected by accuracy in basketball jump shots (Ripoll, Bard & Paillard, 1986).

Significantly longer durations were observed in successful shots compared to unsuccessful ones.

Skill differences in QE duration have been found in a variety of gaze behaviour tasks in other movement environments, such as billiards (Frehlich, 1997), basketball (Ripoll, Bard & Paillard, 1986; Vickers, 1996a), volleyball (Vickers & Adolphe, 1997), golf (Vickers, 1992), and soccer (Williams & Davids, 1998), however this did not occur in the present study. In each of these studies the higher skill participants performed skills very similar to those experienced in competition. All had achieved competitive statistics that placed them in the higher levels of accuracy. The table tennis task selected here was not entirely similar to that performed in competitive table tennis and differed in important respects that may have affected QE duration.

The hypothesized significant difference in EHS was also not found. The expected longer durations of EHS for the high skill group and during hits were not supported by the present findings. As EHS is a mechanism used by top level players (Ripoll & Fleurance, 1988), a longer duration of EHS for the high skill group as compared to low skill group would reflect the ability to stabilize vision prior to ball-bat contact and perform successful returns. The absence of skill level and accuracy effects may be related to the time available from the serve to the ball-bat contact. The total duration of ball flight in the current study characterized a relatively easy type of serve. Although Ripoll and Fleurance (1988) did not report ball flight durations, the time available for world class players from opponent's ball-bat contact and theirs is clearly shorter than the duration used in the present study. This argument is consistent with the difference in EHS durations of 220-375 ms reported in that study and the ones observed in the present study.

One reason for the lack of differences in QE and EHS durations between high and low skill groups in the present study could be related to the skill levels of the participants. The high skill group may not have had sufficiently high skill levels to show such differences. High skill participants were not world class level players, as was the case in studies by Bootsma and van Wieiringen (1990), Ripoll and Fleurance (1988), and Vickers and Adolphe (1997). Vickers' approach (Vickers, 1996a; Vickers & Adolphe, 1997) of using participants with similar physical attributes (experts and near-experts) succeeded in observing differences in gaze behaviour between these groups. Although three participants in the current study were highly ranked regional and national level players none had competed beyond this level in the high skill group. Their QE durations also did not differ from those of the other players. The observation that the high skill participants were overall lesser skilled than in previous studies of a similar nature is supported by Bootsma and van Wieringen (1990) where the elite players' accuracy was 75% to non-cued targets. Table 2 showed that the range of the high skill group's accuracy in the situation without eye tracker was from 44.4 to 79.4%, with mean of 61.3% (SD = 12.2).

A second reason for the lack of significant differences due to skill in QE duration may have been the uniqueness of the table tennis task in the current study. In previous studies by Ripoll (Ripoll, Bard & Paillard, 1986; Ripoll & Fleurance, 1988), Bootsma (Bootsma & van Wieringen, 1988, 1990), and Vickers (Vickers, 1996a; Vickers & Adolphe, 1997) both elite and non-elite performed skills similar in nature to those found in competition. Essential questions focus on the comparison between skill levels and are "what proportion of the expert's skill is tapped by any one lab task and what proportion of the expert-novice difference can be reliably explained by the task" (Starkes, 1993, p. 8). In the current study, hitting to cued targets may not have been sufficiently similar to game conditions to create the expected expert's advantage. In this sense, the results may be similar to Chase and Simon (1973a, 1973b) who found that master chess players' performance was at an elite level only when the task maintained the meaningful arrangement of chess pieces. When a chess master had to remember the layout of pieces during the middle stages of a chess game, they recalled many more pieces correctly than either a class A player or a beginner did. However, the chess master's memory for randomly placed pieces was actually worse than that of lesser skilled players.

The hypothesized higher arm velocity (AVC) of the high skill group is not supported by the findings of this study. However, AVC was higher during misses than hits (Figure 34) for both high and low skill groups. This can be explained by the principle of speed-accuracy trade-off (Fitts, 1954). Fitts' law implies an inverse relation between the difficulty of a movement and the speed with which it can be performed. Since the original work of Fitts, researchers have studied the speed-accuracy trade-off in a variety of contexts revealing that this principle shows remarkable generality (Schmidt & Lee, 1999). It holds for discrete and continuous movements, for children, young and older adults, for arm, hand, finger and foot movements, and for distinct tasks, such as pointing, reaching, and grasping objects of different sizes. In this study, a participant's choice of an excessively fast arm movement was more likely to produce misses. As the size of the target was kept constant, increased arm velocity made the control of positioning the bat relatively more difficult, decreasing spatial accuracy on the target.

The underlying reasons for differences in gaze behaviour between experts and beginners/ near-experts and success rates are not clear. It is argued that focusing attention on the most relevant sources of information and knowing where and when to look are advantageous and a more efficient search strategy of skilled performers (Williams, Davids & Williams, 1999). Consequently, gaze and arm patterns of higher skilled performers should differ from low skilled participants, and following the same reasoning, should also differ between hits and misses. It is possible that although participants were in an environment similar to the ones used in table tennis games, the novelty of specific target areas, cue-lights, a slightly heavier ball and a discrete task (one serve at a time) may have affected the visual patterns of gaze and arm behaviour, masking skill differences.

In sum, the expected effects of skill level and accuracy on gaze behaviour are not fully supported by the results in the present study, except by the observed Accuracy X Skill interaction for QE onset. The time of initiation of QE seemed to matter more than its duration, in terms of the effects of skill and accuracy. Also, a significant effect of accuracy on arm action was found. Hits were characterized by a slower arm action at the contact as predicted by the speed-accuracy trade-off.

Effects of Cue Condition

The effects of the later cue presentation was shown in Figure 26 for the gaze relative to the ball edge (Figures 26A, 26C, and 26E) and the gaze in space (Figures 26B, 26D, and 26F). In the Pre-cue condition, participants had ample time to detect the cue light, track the ball and move the gaze to the correct side to receive the ball. The movement of gaze was more gradual toward the side that the ball was moving. In the Early-cue condition, participants changed their gaze behaviour and maintained their accuracy by making a fast shift of the gaze to the ball. In the Late-cue condition, participants had to wait for the cue and performed a much smaller movement of the gaze, with higher variability. A period of stability of gaze occurred just before contact in all cue conditions. Effects of cue condition on arm movements were also observed. A general reduction in arm movement amplitude (Figures 30A, 30C, and 30E) and arm velocity (Figures 30B, 30D, and 30F) was observed as the cue was delayed.

In the Pre-cue condition, target onset occurred approximately 1.6 s prior to service plus the participants had ball flight time, an average of 821 ms or a total of 2.4 -2.5 seconds to respond. During the Early-cue condition, mean cue onset occurred 263 ms after service contact, leaving a mean of 521 ms to organize the movement to the appropriate target. In the Late-cue condition, cue onset occurred at 492 ms after the service giving only 327 ms to participants to complete the action. This time was insufficient and accuracy levels declined. Mean accuracy was very similar (48%) in the Pre-cue and Early-cue conditions and decreased to 30% in the Late-cue condition (Figure 7). A duration of 194 ms (521 – 327) approximates a well-documented difference in processing time in the literature. Visual reaction time in motor and other skills has a reported threshold of 150 – 180 ms, below which performance is degraded (Zelaznik, Hawkins & Kisselburgh, 1983; Carlton, 1981a, 1981b). What is additional in the current study is insight into why the system became less accurate in terms of changes in the investigated variables (QE, TMT, EHS, MT, and AVC, Hh, Hh, GC). QE duration was reduced from Pre-cue to Early-cue condition and also from Early-cue to Late-cue condition (Figure 29). QE onset was similar in the Pre-cue and Early-cue conditions, and it occurred earlier in the Late-cue condition. QE offset occurred earlier and earlier as the cue presentation was more delayed (Figure 28). TMT was not used to compensate for constraints on early tracking. EHS duration, onset, and offset did not differ significantly across the three cue conditions. AVC was also reduced from Pre-cue to Early-cue condition, but it did not differ between Early-cue and Late-cue conditions (Figure 33). Both Gh and Hh were similar between Pre-cue and Early-cue conditions and were reduced in the Late-cue condition (Figures 35 and 36, respectively).

The decrease in QE duration seemed to be part of a process to minimize motion, as an attempt to overcome the task constraints imposed by Early-cue and Late-cue conditions. This "freezing" process was also reflected in the decrease in horizontal movement of the gaze (Gh) and head (Hh). These two-dimensional measures indicated the location on the table where gaze and head stopped to move laterally towards the side which the ball was approaching. Gaze moved horizontally 31.0 deg in the Pre-cue, 28.6 deg in the Early-cue and 14.7 deg in the Late-cue condition. From this total, the head contributed 17.1 deg in Pre-cue, 17.7 deg in the Early-cue and 5.3 deg in the Late-cue condition. These differences showed that the delay of the cue forced the gaze and head to stay closer to the cue location. This was confirmed by the measure of the angular distance between line-of-gaze and the cue that came on at cue onset time (GC). GC significantly increased in Late-cue condition, but the increase was not pronounced (only 2.3 deg), indicating that participants tended to wait for the cue before moving their gaze towards the side which the ball was approaching. In the Early-cue condition, GC was 5.3 deg whereas in the Late-cue condition, GC was 7.6 deg. Similar reductions in gaze and head movements have been reported by Sharp and Whiting (1975) in a one-handed ball-catching task. The velocity of the ball was manipulated so that participants had distinct durations to see the ball (what they called "time available for the pick up of information") and catch it. They found that performance improved discontinuously with the allowance of longer viewing durations. Performance levels on catching improved gradually to durations up to 245 ms, remained stable from 245 to 365, and improved again up to 445 ms.

According to these authors, for durations of less than 245 ms, visual information for controlling action was obtained by maintaining eyes and head motionless and having the image of the ball moving across the retina (image-retina system). For durations of more than 365 ms, information was obtained by moving eyes and head to maintain the ball image relatively at the same place on the fovea (eye-head system). Between 245 and 365 ms, when the performance levels were stable, there was a transition phase during which the eye/head system gradually took charge of collecting the information. In the present study, Late-cue was the condition with lower accuracy and smaller gaze and head movements. This relation among accuracy, temporal constraint, and use of gaze and head movements is in agreement with Sharp and Whiting (1975). Although the present study differed from Sharp and Whiting in the total ball flight duration (approximately 750-800 ms vs. maximum of 445 ms) as well as in how the temporal constraints were implemented (cue delay vs. ball velocity), the same pattern of results was observed. The reduction in the time available altered the manner in which visual information was acquired. Another distinction between these studies was that in Sharp and Whiting's study, gaze and head behaviours in each trial were classified as one system, and were not differentiated into gaze and head contributions as occurred in the present study.

Montagne, Laurent, and Ripoll (1993) reproduced the experiment of Sharp and Whiting (1975) with additional variables. In one experiment, they manipulated the type of gaze and head behaviour participants used. There were three conditions. Participants had to track the ball, or to "anchor" their eyes on a diode at 0 deg or 33 deg from ball trajectory, in a protocol with four levels of ball flight duration (260 to 370 ms). They found that the percentage of successful trials decreased significantly in the two most constrained ball flight conditions, especially for the 33 deg anchoring. These results agree with those from the present study that showed that the lowest accuracy percentages occurred in the Late-cue condition, when participants had their gaze farther away from the ball sooner in the trial.

In addition to the minimization of movement, the most extreme level of cue delay caused an earlier acquisition of ball image in central vision. QE onset and offset occurred significantly earlier in the Late-cue condition, which seems to indicate that acquiring ball information as soon as possible could provide additional time for the following requirements in the trial such as the detection of cue light. In volleyball, at least, experts appear to take advantage of an earlier onset of tracking when seeing the ball (Vickers & Adolphe, 1997). Participants apparently used a similar strategy to adapt to the increase in time pressure.

EHS duration did not decrease significantly in the Late-cue condition. The variability of gaze in space also increased in the final part of ball flight (Figure 26B, 26D, and 26F). EHS consistently occurred during the forward phase of arm action. This seems in line with Ripoll and Fleurance's (1988) observations of this mechanism as they did mention that EHS occurred just before ball-bat contact, although these authors did not quantify the duration or onset of MT. The durations of EHS differed between these studies. In the present study, EHS durations were 11.3% (77 ms) in the Pre-cue, 7.9% (88 ms) in the Early-cue, and 8.2% (66 ms) in the Late-cue condition whereas Ripoll and Fleurance's were 220, 375, and 238 ms, respectively, for backhand, forehand, and forehand with top spin conditions.

Durations of head and eyes stabilization on target in basketball shooting were approximately (values not reported, visually deducted from figure) 110 ms during hits and 80 ms during misses (Ripoll, Bard & Paillard, 1986). Vickers and Adolphe (1997) noted that only their expert participants exhibited a similar behaviour to eye-head stabilization, stopping tracking within 109 ms prior to ball-arm contact in a volleyball reception. They argued that since the threshold of visual reaction time is 150-180 ms, it was unlikely that visual afference arising during that period of time could affect the passing action.

The present study allowed EHS durations as short as 50 ms. The time required to use visual information translated into action control is usually accepted as the duration of a visual reaction time, as argued by Vickers and Adolphe (1997) and many others (e.g., Carlton, 1981a; Zelaznik, Hawkins & Kisselburgh, 1983). However, some studies have shown the influence of visual information on performance in intervals shorter than 100 ms before contact (Bootsma & van Wieringen, 1990; Lee, Young, Reddish, Lough & Clayton, 1983; Whiting, Gill & Stephenson, 1970). In this study the coordinated system "broke down" when only 321 ms was left to detect the cue and perform the action.

It is particularly interesting that EHS occurred during MT, in the final portion of ball flight because time-to-contact information has been argued to be effective in the final 250-300 ms of interceptive actions (Lee, 1980; Lee et al, 1983). Bruce and Green (1990) suggested that during this interval it would be important to view the ball in flight, since it is during this time that the variable tau (Lee, 1980) would be used to give an accurate measure of time-to-contact, while still allowing enough time for orienting movements to occur. In the present study, the period of EHS was characterized by the ball moving away to peripheral vision as the gaze was relatively stationary at that time (compare Figures 26A, 26C, and 26E with 26B, 26D, and 26F, respectively). Assuming that visual information can be used in action control within intervals shorter than a visual reaction time, the function of EHS could be as follows. As the perception of information contained in the optic flow does not necessarily require central vision (Gibson, 1979/1986), the period of EHS could provide stability of the all visual scene and balance (Lee & Lishman, 1975) and, simultaneously, sensitivity to ball motion through peripheral vision (Bruce & Green, 1990; Schwartz, 1994). Also, the variable tau could provide appropriate time-to-contact information in this interval even if the ball was not approaching in a straight trajectory to the eye (Bootsma & Peper, 1992). On the other hand, if a visual reaction time is necessary to use information in action control, EHS could provide mechanical stability of head and therefore contribute to optimal posture to support the fast arm action. Head positioning has been shown to affect encoding of target location and accuracy of aiming (Bard, Fleury & Paillard, 1990).

An additional aspect of the functionality of EHS is that the present study used only gaze in space to compute EHS onset and offset. If, in fact, the head continued to move (which was not specifically measured) during the period of EHS, maintenance of gaze position could be accomplished via VOR, as has been suggested by Lee & Zeigh (1991).

MT duration was not affected by the cue manipulation. Consistency of MT in highly practiced skills has been demonstrated in a variety of situations, such as in baseball (Hubbard & Seng, 1954) and table tennis (Tyldesley & Whiting, 1975). Constant MTs are advantageous in terms of timing action to an external object or event because it reduces the decisions involved in this process, as proposed by the operational timing hypothesis of Tyldesley & Whiting (1975). A well-practiced skill has its duration learned and the performer has only to specify the moment of movement initiation. Thus the decision requirement is reduced and one degree of freedom can be freed up in the perception-action relation.

Bootsma and van Wieringen (1990) showed that small variations in MT and other movement variables served functional purposes in a table tennis study. They found that fluctuations in one perceptual variable (tau margin) were compensated for by fluctuations in a movement variable (mean arm acceleration), showing a relation called compensatory variability by the authors. In the present study, MT did not change even under the task restraints of the three cue conditions, which was an unexpected result. The velocity at contact did change, however, but MT remained invariant. These results agree with those from Bootsma and van Wieringen (1988, 1990). They argued that if repeated table tennis strokes are to be regarded as repeated execution of the same movement pattern, as the motor program theory (e.g., Schmidt, 1988, 1991) states, the occasions on which the stroke was initiated somewhat earlier in time should be positively correlated with larger velocities at ball/bat contact. However, a negative correlation between these motor and perceptual components was found and interpreted as a compensatory coupling. In the present study, following the same rationale, similar MT should produce similar AVC, which did not occur. The reduction in AVC was also compensatory to allow adaptation to the imposed time constraints. Two other aspects should be considered on this topic. First, the amplitude of the movement, which was apparently reduced in the Late-cue condition, could also be related to the control of arm movement duration and velocity. Secondly, there was an important difference between Bootsma and van Wieringen (1988, 1990) and the current study. Their participants were reaching maximum velocity at the contact whereas the participants in the present study reached maximum velocity before contact and were reducing velocity at the contact. Control of deceleration may have played a significant role in the contact control (Teasdale & Schmidt, 1991).

In the present study the delay in cue presentation did not effect the duration of MT. However another interesting mechanism, compensatory in nature, was observed in the arm action. As the time constraints were increasing, participants initiated (in the absolute time scale) the forward arm motion later (Figure 31). This strategy provided participants with extra time to detect the cue before starting the constant MT. It is important to remember that participants stayed at the centre position at serve and then were allowed to move, which probably facilitated the spatial and temporal adjustments in arm motion to achieve these later MT onsets. Furthermore, AVC was reduced in the Early-cue and Late-cue conditions (Figure 33) and the amplitude of arm movement (Figures 30A, 30C, and 30E) seemed to decrease in order to adapt to the difficulty of the harder cue conditions.

Cue condition did not affect just the duration of gaze behaviours, but also their occurrence in a trial (Tables 3 and 4). The delay of the cue generated an increase in the absence of gaze behaviours in both groups. Ripoll and Fleurance (1988) also reported the absence of tracking and EHS for some participants. Interestingly, these cases of absence differed across the experimental conditions of that study (backhand, forehand, and forehand with top spin drives), indicating, in a manner similar to the present study, that the absence of a gaze behaviour was due to the specific task constraints. When the absence of QE and EHS was most frequent (Late-cue condition), the accuracy was lowest.

Functions of QE and EHS

QE and EHS functioned, respectively, to first stabilize the ball image and then the scene view prior to arm contact. QE and EHS were both present in most trials in the Pre-cue and Early-cue conditions, but one or the other (especially EHS) was absent in the Late-cue condition. The general functions of gaze behaviour in the present study reflected the importance of gaze stabilization as proposed by Owen and Lee (1986). Minimization of instability of the visual image is advantageous for optimizing the acquisition of information (Daniel & Lee, 1990).

Vickers (1996a) has argued that "the duration of QE plays a key role in the optimal organization of the neural structures underlying" motor skills (p. 352). QE duration was 400 ms (52%) of ball flight duration in the Pre-cue condition, 264 ms (33%) in the Early-cue condition, and 182 ms (22%) in the Late-cue condition, a significant decrease. She also suggested that "if quiet eye duration is a critical factor in the organization of the neural structures underlying aiming at far targets, then experimental reduction of this time should result in a decrease in performance" (p. 353). Experimental reduction of QE by Frehlich (1997) also showed similar results. The results of the present study indicated a significant reduction of QE duration due to the experimental manipulation of the time of cue presentation. There were differences between basketball free shooting and the particular table tennis stroke required in this study, which might also have affected performance. In basketball, the ball was on the participant's hands and there was only one target. In this table tennis task there were three types of "targets" (or critical objects/locations) in the same situation: two possible target areas on the opposite side of the net, the ball in motion, and two possible set of cue lights.

The duration of QE is the time in which central vision of a location or object is needed to set the parameters of a subsequent action adequately, such as location and distance to the target, ball trajectory, optimal forces required throughout the movement (Vickers, 1996a; Vickers & Adolphe, 1997). In this context, the present study asked the question: What are the consequences of delaying the information regarding one specific parameter (right or left direction of ball return) of action to occur? The results indicated that changes in accuracy on the target depended on the extent of the delay. A small delay (Early-cue) caused few adaptations on gaze and arm behaviour, but did not affect accuracy levels. A longer delay (Late-cue) however was problematic in terms of maintaining accuracy, and generated a number of adaptations described previously. It is worth noting that the manipulation of the cue delay was associated with distinct distances between the cue light and the table tennis ball, once it was not technically possible to isolate these effects in the experiment.

Ripoll and Fleurance (1988) described the mechanism of EHS in table tennis as relatively close to the one reported by Haywood (1984). It was shown that the temporal estimation of the moment of impact of a mobile object upon a fixed target improved when gaze was on the fixed target (image-retina system) compared to when gaze followed the mobile target (eye-head system) (Haywood, 1984). Pre-positioning the gaze around the future ball-bat contact position in table tennis, as shown in the results of the present study, supported this notion (Ripoll & Fleurance, 1988).

Conclusions

The present study made methodological and theoretical contributions to our understanding of visuo-motor coordination. The three-dimensional kinematics of simultaneous line of gaze, head, arm, and ball motion was quantitatively described in a natural environment for the first time. Several interesting findings on how participants controlled their gaze and arm behaviours to return a table tennis ball to a cued target on the opposite side of the net were obtained with this method.

The manipulation of cue onset time showed the limits of adaptation in the investigated motor and perceptual components to maintain spatial accuracy on the target. When participants had approximately 520 ms to identify the cue and respond in the Early-cue condition, the accuracy was maintained as when the cue was seen prior to serve (Pre-cue condition). To accommodate Early-cue levels of spatial and temporal constraint, participants reduced the duration of QE, terminated QE earlier, and hit the ball slower. However, when participants had only approximately 320 ms to detect the cue and act (Late-cue condition), the accuracy decreased considerably and a variety of changes in gaze and arm behaviours was observed. The decrease in movement was generalized for gaze, head, arm position and arm velocity. Participants seemed to "freeze" as an attempt to preserve accuracy in such constrained situation.

In terms of gaze behavior, the most delayed cue condition not only caused the decrease in duration of QE but also a decrease in the frequency of QE and EHS. Although the amount of movement was reduced for gaze, head, and arm, participants were much more frequently unable to keep both the ball image stable during the preparation phase and the gaze stable during the execution phase of arm action. In terms of arm movement, the time pressure made participants to delay (in absolute time scale) the initiation of arm forward phase. The present findings also indicated that slower arm movement was associated with higher levels of accuracy on the target.

A late tracking on the ball was not a characteristic of skill level or accuracy. TMT was virtually non-existent in the present table tennis task. Instead, an early tracking onset was linked to accuracy and skill. No expertise advantage was found in gaze and arm movements, even in the Late-cue condition. The high skill group did respond more accurately in the more extreme situation, but their superiority was not reflected in the variables accessed in this study. Perhaps this would not have occurred with world class players.

Future Directions

It is traditionally assumed that vision in humans has a single function, namely, to generate a unified representation of the external world. This representation would provide the perceptual foundation for visually based thought and action (e.g., Fodor & Pylyshyn, 1981). From this perspective, visual scientists are interested in the question of how the spatio-temporal mosaic of light striking the retina is transformed into the array of objects and events that compose the observer's perceptual experience of the world. The processes involved in this transformation are typically regarded as part of a single system dedicated to generate a unified percept of the world. Although this approach to vision has produced considerable empirical and theoretical advances, it largely ignores the ultimate function of vision to ensure an effective and adaptive behavioural output (Milner & Goodale, 1995).

A notable exception to the traditional information processing approach is the work of James J. Gibson (1979/1986) who emphasized the importance of vision in the control of action. Vision, in the Gibsonian view, provides information about objects and events in the external world and also plays an essential role in monitoring changes in the visual array that result from the perceiver's action in the environment (Turvey, 1977a, 1977b). In contrast to the traditional view, Gibson's notion of direct perception does not depend on constructive perceptual and cognitive processes based on the stimulating mosaic of light. Instead, the richness of the stimulation itself provides an accurate specification of the nature of objects, places and events. An active perceiver continuously changes the point of observation in space and its relation to the environment generating an optic flow on the retina that is informative and allows adequate control of action (Lee, 1980;

Michaels & Carello, 1981).

Are There Distinct Visual Systems for Perception and Action?

An alternative view to the approaches mentioned above, based on neurophysiological studies suggests that vision has two distinct functions. Investigations on two visual systems emerged in the late 1960s. Trevarthen (1968) identified two areas in the brain and their respective visual functions: the midbrain system that mediates "ambient" vision and the geniculostriate system that mediates "focal" vision. Ambient vision was thought to guide whole body movements, such as locomotion, and focal vision to guide object perception and fine motor acts, such as manipulation. The importance of this work was in stating that the visual pathways did not constitute a unitary system but instead consisted of at least two relatively independent channels from the retina to the brain.

Schneider (1969) hypothesized a somewhat different two-system model. He postulated an anatomical separation between the visual coding of the location of a stimulus and the identification of that stimulus. He attributed location coding to the ancient retinotectal pathway, and the identification of the stimulus to the newer geniculostriate system. However, the notion of localization failed to distinguish between the many different patterns of behaviour that vary with the spatial location of the visual stimuli, only some of which turn out to rely on tectal mechanisms (Goodale & Milner, 1982; Ingle, 1982). Although Schneider's specific proposal is no longer generally accepted, the distinction between object identification ("what") and spatial localization ("where") has strongly persisted in this area (Goodale & Milner, 1992).

Ungerleider and Mishkin's (1982) "two cortical visual systems model has been the most influential account of higher visual organization in neuroscience throughout the 1980's." (Milner & Goodale, 1995, p. 23). They concluded that the appreciation of qualities and of the spatial location of an object depends on the processing of different kinds of information. The processing of qualities occurs in the inferotemporal cortex while the processing of spatial location occurs in the posterior parietal cortex. Evidence was presented to suggest that these two areas receive independent sets of projections from the striate cortex. They distinguished between a "ventral stream" of projections that eventually reaches the inferotemporal cortex, and a "dorsal stream" that terminates finally in the posterior parietal region. The resulting "what" and "where" dichotomy is therefore similar to that of Schneider's, a dorsal parietal stream responsible for object identification (what) and a ventral, inferotemporal stream responsible for spatial location (where). But although, Ungerleider and Mishkin (1982) made the same functional distinction between identification and localization as Schneider (1969), they mapped it into the diverging ventral and dorsal streams of output from the striate cortex. Thus, the emphasis in Ungleider and Mishkin's (1982) model was a distinction based primarily on stimulus attributes or features which focuses on the decision about the stimulus array (Goodale & Milner, 1992; Milner & Goodale, 1993, 1995).

The ventral and dorsal projections streams identified by Ungerleider and Mishkin (1982) were thought to represent the continuation of the parvo and magno systems, respectively. Livingstone and Hubel (1988) proposed that the parvo channel remains independent from the eye to the inferotemporal cortex while the magno channel runs in a quite separate course from the retina through to the posterior parietal cortex. In other words, Livingstone and Hubel (1988) indicated that Ungerleider and Mishkin's "what" and "where" pathways could be associated with the cytological subdivisions of the pars dorsalis of the lateral geniculate nucleus. They suggested that the magno system was primarily related to the global spatial organization, localizing objects in the visual field, as the parvo system played an essential role in object identification, analyzing the scene in greater detail, being sensitive to shape, colour, and surface properties of objects.

Milner and Goodale's Two Visual Systems

Goodale and Milner (1992, p. 20) have proposed a new account for the hypothesis of two visual systems:

> Accumulating neuropsychological, electrophysiological, and behavioural evidence suggests that the neural substrates of visual perception may be quite distinct from those underlying the visual control of actions. In other words, the set of object descriptions that permit identification and recognition may be computed independently of the set of descriptions that allow an observer to shape the hand appropriately to pick up an object. It is proposed that the ventral stream of projections from the striate cortex to the inferotemporal cortex plays the major role in the perceptual identification of objects, while the dorsal stream projecting from the striate cortex to the posterior parietal region mediates the required sensorimotor transformations for visually guided actions directed at such objects.

Milner and Goodale's (1995) model departs from previous models in defining two different functions for visual information. Earlier models by Trevarthen, Schneider, Underleider and Mishkin were input models that identified one visual system as finding objects in space (where) and a second for recognizing these objects (what). None of these models explained how visual information contributed to response production. In contrast, Milner and Goodale's two-system approach is an output model. It posits a separate ventral visual system for the purposes of object perception and representation in space and a second dorsal system, which uses this visual information in formulating an effective response. Integral to the theory is the differential coding of visual information after it leaves the occipital areas; visual inputs are transformed for different purposes – one for representing visual information and another for using vision to guide action.

Milner and Goodale have argued that two separate networks of areas have evolved in the primate visual cortex, a perceptual system, which is indirectly linked to action through cognitive processes, and a visuomotor system, which is intimately linked with motor control (Milner & Goodale, 1995). In evolutionary terms, their argument is that vision evolved in vertebrates and other organisms not to provide perception of the world per se, but to provide distal sensory control of the movements of these organisms. According to these authors, natural selection cares little about how well an animal "sees" the world, but a great deal about how well the animal searches for food, avoids predators, finds mates, and moves efficiently in the environment (Milner & Goodale, 1993). Milner and Goodale's model is centered on the notion that the reason for two cortical pathways is that each must transform incoming visual information for different purposes.

Milner and Goodale (1995) based their model on the existence of anatomical distinction between a dorsal stream projecting to the posterior parietal lobe and a ventral stream projecting to the inferotemporal cortex, as well as neuropsychological studies that posit separate functions for the two systems. Previous models, such as Ungerleider and Mishkin's (1982) and Livingstone and Hubel's (1988), focused entirely on the differential processing of incoming visual information in the two visual pathways. The products of this processing from each pathway were seen as contributing to a single combined representation of the visual world (Milner & Goodale, 1993). Milner and Goodale's perspective puts less emphasis on input distinctions and more on the output characteristics of the two cortical systems. For example, in a task such as reaching and grasping an object, coordination between movements of the fingers, hands, upper limbs, torso, head, and eyes is required. The visual inputs and transformations necessary for the orchestration of these movements will differ in important respects whether they are leading to the identification and recognition of objects or events in the world. To fixate and then reach an object, its location and motion have to be specified in egocentric coordinates (i.e., coded with respect to the observer). The particular coordinate system used (centered with respect to the retina, head, or body) will depend on the specific effector to act (eyes, hand, or both). In addition, as the relative positions of object and observer can change over time, these egocentric coordinates must be computed continuously. This suggests that the dorsal vision-for-action system may have a very short memory (Goodale & Milner, 1992; Milner & Goodale, 1993, 1995).

In clear contrast to the viewer-based coding required for visuomotor control, visual coding for purposes of perception must produce the identity of the object independent of any particular viewpoint in space, that is an "allocentric" view. The essential problem for the perceptual system is to code, and then extract, object identity. The constancies of shape, size, colour, lightness, and location that characterizes human visual perception enable the enduring features of objects to be maintained across different viewing conditions. Processing of this type is likely to involve a long-term storage and attached memory processes (Goodale & Milner, 1992; Milner & Goodale, 1993, 1995).

Despite the apparent independence of the two streams, coordinated action is dependent upon a high degree of cooperation between the two pathways (Milner & Goodale, 1995). The selection of targets for prehension and the use of stored object information in the programming of the act of prehension itself are examples of cooperative action. Grasping an object is the result of a complex interaction of many different brain systems ranging from motivation, through the decision, to movement execution itself; the transfer of high-level visual information between the two streams probably occurs in an early stage of this process. Although the dorsal stream is thought to carry out the necessary computations for efficient on-line control, a necessary first prerequisite to execution of an action is the selection of a goal object/target to be addressed. At this time the object/target is "flagged" in some way during processing by ventral stream. The second prerequisite is to convey whatever "top-down" knowledge about the object/target is needed to supplement the "bottom-up" sensory information used routinely by the dorsal stream (Milner & Goodale, 1995). The process of "flagging" a goal object/target as mentioned above is perhaps caused by an enhanced "attentional" activity (Milner & Goodale, 1995).

Theories of Two Visual Systems and the Present Study

Milner and Goodale (1995) provide a theory of two functionally distinctive visual systems. They propose a ventral system (vision-for-perception) that is responsible for object identification, and a dorsal system (vision-for-action) that provides information in egocentric coordinates for controlling of movements. Ripoll (1991) also proposed that vision has two distinct functions. A semantic visual function that identifies and interprets the situation, and a sensorio-motor visual function that carries out the motor responses. EHS, for instance, is a mechanism linked to the sensorio-motor function, which provides information for action control. In trying to apply the notion of two visual systems to the gaze behaviour in the current study, one could think of relating the semantic, vision-for-perception system to QE and relating the sensorimotor, vision-for-action system to EHS.

QE is the time of setting action parameters (Vickers, 1996a), which is normally interpreted as related to cognitive activity (e.g., Schmidt & Lee, 1999), and occurs when the ball has not yet arrived into the space where the participant can act. It has been shown that QE duration increases as task cognitive complexity increases in billiards (Frehlich, 1997). EHS occurs during MT when the ball position needs to be specified in space with respect to the participant. EHS was defined as a mechanism linked to sensorio-motor function that supports the motor actions (Ripoll, 1991). In addition, during QE, the ball is maintained in central vision whereas during EHS the ball and most of the scene of interest are in peripheral vision. Goodale and Haffenden (1998) reviewed behavioural observations of the two visual systems in humans and concluded that they were "consistent with anatomical and electrophysiological studies in the monkey showing that areas in the dorsal stream receive extensive inputs from the peripheral visual fields while inputs to the ventral stream are largely from more central regions of the visual field" (p. 291).

Although these described functions of QE and EHS seem in general to agree with, respectively, ventral and dorsal systems, there are several aspects that are not clear. Milner and Goodale's model suggest that each system is used according to the purpose of visual processing at that situation. The overall indication is that if the purpose is perception, the system to be used is the ventral system; if the purpose is controlling action, the system to be used is the dorsal system. However, the model does not clearly specify how cognition can be combined with action in terms of the two systems. In this case of combination between perceptual and motor aspects, such as in the present table tennis task, the model does not indicate specifically how and when a shift between the systems would or can occur. The only information on this matter is the notion that a cooperation between the two systems should occur around the time of movement initiation, which should coincide with an increase on attentional activity.

At least two important questions can be asked regarding the role of cognition in tasks like the one studied here. First, why is it necessary to imply cognitive activity in a task such as table tennis stroke? The issue of how cognition participates on perception and action has been debated extensively for decades (e.g., Fodor & Pylyshyn, 1981; Gibson, 1979/1986; Marr, 1982; Schmidt & Lee, 1999; Turvey, 1977a, 1977b). For the purposes of this study, it is possible to acknowledge the visual processing via the dorsal system throughout a trial, without using a cognitive argument. According to Milner and

Goodale (1995), the visual processing involved in cue identification is clearly attributed to the ventral system. Since the current study was unable to access these systems directly, one is unable to state with assurance, in either direction.

Secondly, if there is cooperation between the two systems at the time of movement initiation, to which movement initiation does the model refer? There are several movements occurring simultaneously in the present table tennis task, such as postural adjustments in terms of trunk and legs, head, eye, and arm movements (with backward and forward phases).

A. D. Milner (personal communication, February 17, 1999), regarding this type of tentative relation between the two visual systems and variables in the present study, said that these

> "intuitions about dorsal/ventral control seem pretty reasonable .... But even though you have an interesting experimental environment that is as well controlled as you could get, it is still a highly complex situation. One of the big puzzles for me is how the programming of the strike will modulate the visual processing going on simultaneously with that planning. I would guess that if the actor simply had to catch the ball, we'd be looking at much more dorsally dominated processing; but since s/he has to hit it with a particular direction and amplitude, I would imagine a heavier cognitive load that probably recruits ventral processing - though that's sure to be a function of degree of expertise. My problem in not being more precise is that we are still chipping away at trying to delineate the roles played by the two streams, and doing that is a difficult and long-term

empirical enterprise. For instance, I wonder how our agnosic patient DF would perform in your task ... my guess is that she could hit the ball OK but not direct it well."

It seems that the development of the theoretical argument in favour of the two visual systems does not allow them to be distinguished in terms of QE and EHS. Future research on the characteristics of ventral and dorsal visual systems and gaze behaviour in complex situations may clarify such associations. One could approach this problem in future studies by preventing or restricting ventral (QE) processing and/or dorsal (EHS) beyond what was done here. Also left to future investigations is a determination of the relative contribution of the visuo-motor coordination variables described here to accuracy.

Visuo-motor Coordination

The results reported in the present study showed that controlling gaze during the preparation and execution phases of a stroke in table tennis under distinct levels of task constraints required the participants to govern the interactions among perceptual and motor variables of the skill.

Relevant visual information to plan and execute action was not acquired effortlessly. Looking for the most meaningful and informative portions of the visual scene is an activity of eye and head that supports appropriate responses. "The visual system *hunts* for comprehension and clarity" (Gibson, 1979/1986, p. 219). An active perceiver continuously explores the environment using eyes, head, and body movements, like participants of this study that first tracked the ball and then hit to the target, as gaze was stable.

"The process of mastering redundant degrees of freedom of a moving organ" (Bernstein, 1967, p. 127) that occurs when someone is playing table tennis, for example, necessarily involves the active visual exploration of the scene via control of combined gaze and arm movements. A moving organ has available multiple possibilities to explore and acquire visual information and multiple possibilities to generate compatible motor actions into a context. Visuo-motor coordination is a process of organization of these possible combinations between visual information acquisition and action.

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