Head, eye and arm coordination in table tennis

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The aim of this study was to determine the role of head, eye and arm movements during the execution of a table tennis forehand stroke. Three-dimensional kinematic analysis of line-of-gaze, arm and ball was used to describe visual and motor behaviour. Skilled and less skilled participants returned the ball to cued right or left target areas under three levels of temporal constraint: pre-, early- and late-cue conditions. In the pre- and early-cue conditions, both high and low skill participants tracked the ball early in flight and kept gaze stable on a location in advance of the ball before ball–bat contact. Skilled participants demonstrated an earlier onset of ball tracking and recorded higher performance accuracy than less skilled counterparts. The manipulation of cue condition showed the limits of adaptation to maintain accuracy on the target. Participants were able to accommodate the constraints imposed by the early-cue condition by using a shorter quiet eye duration, earlier quiet eye offset and reduced arm velocity at contact. In the late-cue condition, modifications to gaze, head and arm movements were not sufficient to preserve accuracy. The findings highlight the functional coupling between perception and action during time-constrained, goal-directed actions.

Keywords: gaze behaviour, interceptive actions, skill, visual perception.

Introduction

Successful performance in interceptive tasks depends upon the acquisition of visual information about the approaching object. An athlete who looks in the right place at the correct time is more likely to predict accurately the ball’s future trajectory and time of arrival. Information on gaze behaviour may, therefore, indicate which parts of ball flight are important because ‘the best information about the position and velocity of approaching objects comes from the fovea and its vicinity’ (Land and McLeod, 2000, p. 1341). When trying to intercept an approaching object, athletes also have to deal with the time latency necessary to adjust motor commands based on visual information. For example, in the table tennis serve, ball flight time is approximately 800 ms, during which time the opponent must select an appropriate trajectory for the racket based on information available early in ball flight. Visual information from late ball flight may also help players to refine estimates of ball position and velocity. Our main aim in this study was to determine how players coordinate head, eye and arm movements to acquire the necessary visual information for successful performance on a table tennis task. A secondary aim was to determine whether head, eye and arm coordination varies as a function of expertise and temporal constraint.

A considerable amount of research has focused on gaze control during the performance of sport skills. Several characteristics of performance have been investigated, including visual search (e.g. Bahill and LaRitz, 1984; Haywood, 1984; Abernethy, 1990, 1991), eye–head–arm coordination (e.g. Carnahan and Marteniuk, 1991, 1994; Carnahan, 1992) and gaze–hand coupling (e.g. Helsen et al., 1997, 1998). Also, from a methodological perspective, researchers have progressed from static slide (e.g. Bard and Fleury, 1976, 1981) to dynamic film (e.g. Helsen and Pauwels, 1993; Williams et al., 1994; Williams and Davids, 1998) and field-based protocols (e.g. Vickers, 1992, 1996; Singer et al., 1998; Land and McLeod, 2000). The collection of data in situ represents an important evolution, since the gaze and motor characteristics observed under
laboratory conditions may not provide an accurate reflection of participants’ natural behaviour (Williams and Davids, 1998). Moreover, investigations conducted in situ have revealed important mechanisms and strategies involved in the acquisition of visual information.

One of the earliest studies in the field was undertaken by Ripoll and Fleurance (1988), who wished to determine whether expert table tennis players follow the coach’s instruction to ‘keep your eyes on the ball’. The visuo-motor behaviour of five international players was examined as they performed three different strokes (forehand, forehand with top spin and backhand drive). Experts did not track the ball throughout its entire flight path, preferring only to track the ball at the very beginning of its trajectory. The tracking characteristics observed varied according to the type of stroke. The ball was tracked more often and for longer when it moved towards the midline of the body (i.e. backhand drive) compared to when it moved laterally in relation to the body (i.e. forehand and forehand drive with top spin).

During the final portion of ball flight, Ripoll and Fleurance (1988) observed the mechanism of eye–head stabilization. Before ball–bat contact, between the final ball bounce and the strike, the eyes were stable and aligned with head orientation. The head and eyes were stabilized on the area of ball–bat contact before the ball’s arrival. This occurred more frequently for successful shots, particularly when the ball was projected laterally to the body. The participants’ visuo-motor behaviours were constrained by external characteristics such as ball trajectory eccentricity in relation to the midline of the body.

In a study comparing expert and near-expert basketball free throw shooters, Vickers (1996) observed that skilled performers use a unique visuo-motor strategy to achieve success. The experts initiated fixation on the target (hoop) midway through the preparation phase and maintained fixation significantly longer than near-experts. In this context, the notion of ‘quiet eye’ was introduced and defined as the duration of final fixation on a critical location before the initiation of movement. The quiet eye period was assumed to reflect the time spent in programming the ensuing motor response. Quiet eye for the expert shooters was 972 ms on hits and 806 ms on misses, compared with less than 400 ms for the near-expert players on both hits and misses. Clearly, fixating the target early was important, as was holding the gaze steady until the shooting action began.

To study the serve reception and passing skills of volleyball players, Vickers and Adolphe (1997) defined quiet eye as the duration of tracking before the first step to play the ball. Quiet eye for the expert receivers was 432 ms, while the near-experts did not fixate on the ball before initiating a response. The expert receivers did not begin stepping until they had tracked the ball during flight for almost half a second, whereas 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 the duration longer for expert than near-expert receivers. Neither group tracked the ball to contact, supporting other studies on baseball (Bahill and LaRitz, 1984), table tennis (Ripoll and Fleurance, 1988) and tennis (Singer et al., 1998). Near-experts used more corrective steps and received the ball at less optimal locations. These motor behaviours were associated with a failure to track the ball early in flight and an inability to anticipate its future spatial and temporal coordinates (Vickers and Adolphe, 1997).

Recently, Land and McLeod (2000) studied the gaze behaviour of cricket players of differing abilities. Batsmen fixated the point of delivery and their gaze stayed stationary for a period after delivery as the ball entered the field of view. Next, an anticipatory saccade was made and the fovea ‘lay in wait’ (p. 1341) for the bounce; gaze was kept stable for a period before and after the bounce. The ball was then tracked accurately for at least 200 ms after the bounce, and tracked ‘more loosely’ (p. 1342) on the final part of its flight. Although the three participants presented similar gaze strategies, differences were attributed to their differing abilities. The professional player showed more pursuit tracking than the good and the weak amateurs, using an optimal combination of smooth pursuit and saccadic eye movements to get to the bounce point. The weak amateur was slower to respond to the ball’s appearance than the other two batsmen, taking at least 200 ms to initiate a saccade, and the timing of his saccades was also more variable. The authors suggested that the main difference between good (professional and good amateur) and poor (weak amateur) batsmen was the speed and variability of the initial saccade. Moreover, they argued that the difference between the professional and the good amateur was the subtle combination of tracking and saccadic movement used by the professional to locate the bounce point.

Although the studies reviewed have identified important components of performance, methodological difficulties and technological limitations are apparent. To date, no study has examined the coupling between head, eye and limb movements, with reasonable sample sizes, in a realistic and dynamic action environment. Previous studies have recorded visual search or kinematic data independently (e.g. Ripoll and Fleurance, 1988; Bootisma and van Wieringen, 1990; Land and McLeod, 2000); no attempt has been made to examine these measures simultaneously in a sports setting.

In the present study, gaze and arm behaviours were recorded simultaneously and the following variables...
were identified: quiet eye, eye–head stabilization, arm movement time and arm velocity at contact. In keeping with previous studies (e.g. Ripoll and Fleurance, 1988; Vickers, 1996), high skill participants were expected to show longer periods of quiet eye and eye–head stabilization than their less skilled counterparts. Regardless of ability, longer periods of quiet eye and eye–head stabilization were also presumed to be associated with successful compared with unsuccessful responses (Ripoll et al., 1986; Vickers, 1996; Vickers and Adolphe, 1997). It was also predicted that the high skill participants would use higher arm velocities at contact, as observed previously in a sample of elite table tennis players (e.g. Bootsma and van Wieringen, 1990). The cueing delay was set to perturb the visuo–motor system and explore possible effects of inherent spatial and temporal task constraints. To examine the limits of visuo–motor adaptation, the cue highlighting the target area was presented under three temporal conditions, which progressively reduced the amount of time available to detect a cue light and execute arm action (pre-, early- and late-cue). Such an approach has not been used previously to study the coupling between visual and motor systems during an interceptive task; consequently, this study was partly exploratory in nature.

Methods

Participants

Sixteen adults volunteered for the study. As recommended by Whiting (1986), the participants were selected using a within-task criterion, the mean accuracy (percentage of hits) across all four test conditions (pre-cue without the eye tracker, pre-, early- and late-cue with the eye tracker). The high skill group comprised nine participants who recorded performance accuracy scores above 40% (mean ± s = 52.9 ± 14.9%, range = 43.6–67.8%); the low skill group consisted of seven participants with accuracy scores below 40% (31.5 ± 12.9%, range = 29.7–35.6%). The high skill group contained one female and eight males with a mean age of 27.9 years (range = 19–42 years); the low skill group contained two females and five males with a mean age of 26.6 years (range = 21–32 years). An initial screening test indicated that all participants had normal or corrected-to-normal vision.

Apparatus

Vision-in-action system. The vision-in-action system (Vickers, 1996) 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. An Applied Sciences Laboratories 501 Eye Tracker (accuracy of ± 1° and precision of 0.5° of visual angle) 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 Fig. 1.

The eye image (i), which was recorded by the camera on the eye tracker, contains horizontal and vertical axes for pupil and corneal reflection centroids. The corneal reflection is produced by a small helmet-mounted infra-red light source. The top portion of the frame (ii) was

Fig. 1. A frame of video recorded with the vision-in-action method containing the eye image (i), the participant’s view (ii) and external view (iii).
recorded by the scene camera attached to the helmet and shows the participant’s location of gaze relative to the environment. Location of gaze is indicated by the white cursor. The bottom portion of the frame (iii) shows the participant performing the table tennis task as recorded by the external camera.

Magnetic head tracker system. Interfaced to the vision-in-action system was a magnetic head tracker, developed by Ascension Technologies (Model Flock of Birds), to provide the three-dimensional position and orientation of the eye tracker helmet relative to a transmitter. The magnetic head tracker had a static positional accuracy of 2.54 mm, a positional resolution of 0.76 mm, a static angular accuracy of 0.5° and angular resolution of 0.1°. The data from the magnetic head and eye tracker were combined (through eye–head integration software) at 60 Hz to generate the participant’s line of gaze relative to the environment.

The motion analysis system. 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 retroreflective markers on each image and reconstructed the three-dimensional position of the markers in space.

Laser device for cue activation. A laser device, placed in parallel alignment with the table tennis net, was used to detect ball passage and activate one of the two sets of cue lights.

Procedures

Calibration. To calibrate the motion analysis system, six cameras were used to record a metal cube with eight reflective markers. A metal wand with markers on each end was then recorded in motion inside the workspace defined by the calibration cube. The EVa generated coefficients specifying the spatial configuration of the reconstructed three-dimensional data.

Eye–head integration calibration was divided into the specification of planes and eye position in space. Spatial coordinates were calculated for planes of interest such as the table tennis table and the eye calibration grid. Participants were then fitted with the eye tracker and positioned in front of the calibration grid. While holding the head stable and moving only the eyes, nine target points were defined in video coordinates in the scene monitor coinciding with those on the calibration grid. Fine calibration for three defined locations on the table tennis surface (coincident with ball trajectory) was performed before each trial.

Experimental task. Figure 2 shows the experimental set-up, including a regulation table tennis table fitted with cue lights and targets. The participants were required to play a forehand drive shot to one of two target areas. The target was cued by a set of lights interfaced to a laser device. An experienced table tennis player was instructed to serve using the same action and velocity for each trial. The patterns of ball flight produced by the server were quite consistent, although the analysis revealed that slightly faster serves were used with high skill participants. The second ball bounce occurred significantly earlier for high (569 ± 43.8 ms) than low skill participants (604 ± 35.2 ms) \( (F_{1,14} = 10.8, P = 0.005) \). The ball was served to the right- or left-hand side depending on whether the participant was right- or left-handed. The target was cued relative to the serve to produce three distinct temporal conditions. The cue light was illuminated before the serve (pre-cue), during the initial portion of ball flight (early-cue) or during the final part of ball flight (late-cue). Overall total flight time (duration from serve to contact) was 792 ms and the participants had means of 2366, 521 and 327 ms to detect the cue light and hit the ball during the pre-, early- and late-cue conditions, respectively.

Data acquisition protocol. The participants were fitted with retroreflective markers attached to the elbow (head of radius) and wrist (ulnar head) of the preferred hand. After a 10-min warm-up with the server, they were tested in one control (pre-cue without the eye tracker) and three experimental (pre-, early- and late-cue) conditions. Trials were recorded until the participants had obtained five hits and five misses or 40 trials were performed in each condition, whichever occurred first. To avoid guessing, ‘catch’ trials were performed at random during data collection. In a catch trial, the cue was not presented and the participants were asked not to respond to the serve. To minimize order effects, the order of presentation of conditions was assigned using a Latin square design (Maxwell and Delaney, 1990). Wearing the eye tracker did not affect the performance of either group \( (F_{1,15} = 0.12, P = 0.73) \). Mean accuracy without and with the eye tracker was 48.9 ± 17.7% and 47.6 ± 15.7%, respectively. The time required to complete all conditions was approximately 45 min.

Data processing. The eye–head integration software provided data for the horizontal and vertical gaze (table coordinate system) and the three-dimensional position and orientation of the head (transmitter coordinate system); the motion analysis system provided the three-dimensional positions of the elbow, wrist and ball (calibration cube coordinate system). The data were smoothed at 5 Hz using a fourth-order Butterworth filter, except for data from the ball that were smoothed at 30 Hz. To transform the eye–head integration data from 60 to 180 Hz, linear interpolation was used for
the gaze data due to the speed and abrupt changes in eye position, while spline interpolation was used for head movements given their relatively slow nature. The coordinate system transformations were based on an algorithm developed by Soderkvist and Wedin (1993). Three angles were calculated from the transformed data sets (see Fig. 3). The visual angle between line of gaze and ball edge (A); visual angle between line of gaze and the x-axis of the transmitter coordinate system (B); and the angle between arm (segment from elbow to wrist) and the x-axis of the transmitter coordinate system (C). A normalization procedure was applied to obtain the time relative to total trial duration (%). Every trial had its onset transformed to 0% (serve) and its offset to 100% (ball–bat contact), and each point in time represented a proportion of the total time (Schmidt and Lee, 1999).

**Dependent variables**

*Percentage of hits.* The percentage of accurate returns to the designated target area (hits) was calculated with respect to the total number of trials.

*Quiet eye onset, offset and duration.* Quiet eye was defined as the duration of final tracking on the ball before the initiation of arm movement (Vickers, 1996). As in previous research (e.g. Ripoll and Fleurance, 1988), the participants were assumed to be tracking when the visual angle between line of gaze and the ball (see Fig. 3A) was maintained within $3^\circ$ for at least 100 ms in each trial. The minimum duration required for visual information extraction was 100 ms, as used by Vickers (1996) and Vickers and Adolphe (1997). Figures 4A, 4C and 4E (left column) show the three-dimensional visual angle ($\text{mean} \pm s$) between line of gaze and the edge of the ball for the pre-, early- and late-cue conditions. The dotted horizontal line indicates $3^\circ$ of visual angle, the threshold for quiet eye.

*Eye–head stabilization onset, offset and duration.* Eye–head stabilization was defined as the stable alignment of the eye and head before ball–bat contact (Ripoll and Fleurance, 1988). For eye–head stabilization to occur, the visual angle between line of gaze and the x-axis of the transmitter coordinate system had to remain stable during the final part of ball flight (see Fig. 3B). Stability was based on a fixation criterion, adapted from Helsen et al. (1998). The onset of eye–head stabilization occurred when the above visual angle was maintained with a standard deviation of $1^\circ$ or less for at least 50 ms in each trial. The offset of eye–head stabilization...
ocurred when four consecutive gaze samples (approximately 22 ms) were farther away than 1.5° from the mean value of the angles within that period of stabilization. A value of 50 ms, less than the limit for quiet eye, was defined based on evidence showing eye–head stabilization periods shorter than 100 ms in basketball beginners (Ripoll et al., 1986) and the potential role of the vestibulo-ocular reflex in eye–head coordination (Guitton and Volle, 1987). Figures 4B, 4D and 4F (right column) show the three-dimensional visual angle (mean ± s) between line of gaze and the x-axis of the transmitter coordinate system for the pre-, early- and late-cue conditions.

Arm velocity at contact. This variable was defined as the angular velocity between the arm (elbow–wrist segment) and x-axis of the transmitter coordinate system at the moment of ball–bat contact (see Fig. 3C). Figures 5B, 5D and 5F (right column) show the arm velocity at contact (mean ± s) for the pre-, early- and late-cue conditions.

Statistical analyses

A one-way analysis of variance was used to examine the effect of wearing the helmet (with, without) and percentage of hits by condition (pre-, early- and late-cue). The remaining dependent variables were analysed using separate skill (high vs low) by cue condition (pre-, early- and late-cue) by accuracy (hit vs miss) mixed-design analyses of variance with repeated measures on the last two factors. Statistical significance was set at \( P < 0.05 \) for all tests. Significant main effects were followed up with pairwise comparisons. Bonferroni adjustments were used for multiple comparisons (Maxwell and Delaney, 1990).

Results

Percentage of hits by cue condition

The percentage of hits differed significantly across the three cue conditions (\( F_{2,47} = 6.53, P = 0.003 \)). Pairwise comparisons showed that accuracy in the late-cue condition (30.3 ± 15.6%) was significantly lower than in the pre-cue (47.6 ± 15.6%; \( F_{1,31} = 9.92, P = 0.004 \)) and early-cue conditions (47.5 ± 15.7%; \( F_{1,31} = 9.72, P = 0.004 \)).

Occurrence of gaze behaviours

The participants did not use quiet eye and/or eye–head stabilization in 144 of 480 trials. Four combinations were possible: quiet eye present and eye–head stabilization absent; eye–head stabilization present and quiet eye absent; both quiet eye and eye–head stabilization present; or both quiet eye and eye–head stabilization
absent. Table 1 summarizes the involvement of each combination during hits and misses in the pre-, early- and late-cue conditions across groups.

**Quiet eye**

For quiet eye onset, analysis of variance revealed a significant two-way interaction between accuracy and skill \( (F_{1,28} = 6.22, P = 0.03) \). The low skill group had a later quiet eye onset during misses \((24.0 \pm 22.7\%\) than hits \((17.7 \pm 20.9\%)\), whereas the high skill group had similar quiet eye onset for hits \((11.7 \pm 18.6\%)\) and misses \((10.0 \pm 15.5\%)\). Quiet eye onset differed significantly across cue conditions \( (F_{2,28} = 8.51, P < 0.001) \). Pairwise comparisons revealed that quiet eye onset occurred significantly earlier in the late- than in the
Fig. 5. Arm angular position (A, C and E) and arm angular velocity (B, D and F) as a function of time (% of trial duration) for the pre- (top), early- (middle) and late-cue (bottom) conditions (mean ± s). Vertical dashed lines on early-cue and late-cue plots represent cue-on time. Movement times were derived from the arm position angle (left column) and arm velocities at contact were derived from arm velocity angle (right column).

early-cue condition ($F_{1,15} = 14.4$, $P = 0.002$). These findings are presented in Table 2.

The period of quiet eye ended significantly earlier as the cue was delayed ($F_{2,28} = 40.3$, $P < 0.001$). All three pairwise comparisons were significant: pre- and early-cue ($F_{1,15} = 11.9$, $P = 0.004$), early- and late-cue ($F_{1,15} = 21.8$, $P < 0.001$) and pre- and late-cue ($F_{1,15} = 83.5$, $P < 0.001$).

The duration of quiet eye decreased significantly as the cue was delayed ($F_{2,28} = 42.6$, $P < 0.001$). All three pairwise comparisons were significant: pre- and early-cue ($F_{1,15} = 40.7$, $P < 0.001$), early- and late-
Table 1. Relative frequency (%) of gaze behaviour combinations as a function of cue condition and accuracy for high and low skill groups (QE = quiet eye, EHS = eye–head stabilization)

<table>
<thead>
<tr>
<th>Skill group</th>
<th>Gaze combination</th>
<th>Pre-cue</th>
<th>Early-cue</th>
<th>Late-cue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hits</td>
<td>Misses</td>
<td>Hits</td>
</tr>
<tr>
<td></td>
<td>QE and EHS</td>
<td>13.3</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>Only QE</td>
<td>1.9</td>
<td>3.0</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Only EHS</td>
<td>1.1</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>No QE/No EHS</td>
<td>0.4</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.8</td>
<td>14.3</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>Only QE</td>
<td>0.5</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Only EHS</td>
<td>0.5</td>
<td>1.0</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>No QE/No EHS</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Quiet eye and eye–head stabilization onset, offset and duration (%), movement time onset and duration (%), and arm velocity at contact (rad·s\(^{-1}\)) in the pre-, early- and late-cue conditions (mean ± s)

<table>
<thead>
<tr>
<th></th>
<th>Pre-cue</th>
<th>Early-cue</th>
<th>Late-cue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet eye onset</td>
<td>15.1 ± 20.2</td>
<td>21.6 ± 23.2</td>
<td>7.5 ± 10.8</td>
</tr>
<tr>
<td>Quiet eye offset</td>
<td>70.6 ± 19.5</td>
<td>59.6 ± 26.6</td>
<td>38.0 ± 13.3</td>
</tr>
<tr>
<td>Quiet eye duration</td>
<td>51.9 ± 26.5</td>
<td>33.4 ± 21.5</td>
<td>22.3 ± 16.7</td>
</tr>
<tr>
<td>Eye–head stabilization onset</td>
<td>84.2 ± 6.8</td>
<td>84.5 ± 6.0</td>
<td>81.1 ± 11.1</td>
</tr>
<tr>
<td>Eye–head stabilization offset</td>
<td>95.7 ± 6.6</td>
<td>96.4 ± 4.8</td>
<td>96.1 ± 5.9</td>
</tr>
<tr>
<td>Eye–head stabilization duration</td>
<td>10.1 ± 5.3</td>
<td>11.3 ± 5.4</td>
<td>7.9 ± 10.4</td>
</tr>
<tr>
<td>Movement time onset</td>
<td>79.0 ± 5.9</td>
<td>80.3 ± 5.6</td>
<td>81.3 ± 6.3</td>
</tr>
<tr>
<td>Movement time duration</td>
<td>21.0 ± 5.9</td>
<td>19.8 ± 5.6</td>
<td>18.7 ± 6.3</td>
</tr>
<tr>
<td>Arm velocity at contact</td>
<td>-1.93 ± 1.08</td>
<td>-1.56 ± 0.94</td>
<td>-1.42 ± 0.79</td>
</tr>
</tbody>
</table>

There was a reduction in arm velocity at contact as the cue was delayed \((F_{2,28} = 7.60, P = 0.004)\). Two pair-wise comparisons were significant: between pre- and early-cue \((F_{1,15} = 10.6, P = 0.005)\) and between pre- and late-cue \((F_{1,15} = 11.2, P = 0.004)\) (see Table 2). In addition, arm velocity at contact during misses \((-1.70 ± 1.02 \text{ rad}·\text{s}^{-1})\) was significantly higher than during hits \((-1.57 ± 0.91 \text{ rad}·\text{s}^{-1})\) \((F_{1,28} = 10.4, P = 0.006)\).

Discussion

This study was a novel attempt to determine how the acquisition of visual information through movements of the head and eyes affects the execution of a complex motor skill. Various gaze behaviours were recorded during the execution of a table tennis forehand stroke under different spatial and temporal constraints. As reported in previous research (Bahill and LaRitz, 1984; Ripoll and Fleurance, 1988; Vickers and Adolphe, 1997; Land and McLeod, 2000), participants kept their eyes on the ball early in flight but not during the final
portion of its trajectory. Before interception, the participants maintained a stable gaze on a location in advance of the ball (cf. Ripoll et al., 1986; Ripoll and Fleurance, 1988; Land and McLeod, 2000). Several new findings emerged that increase our understanding of the effects of skill, accuracy and spatio-temporal constraints on visual information acquisition during the performance of an interceptive task. The effects of skill, accuracy and cue condition are discussed initially, followed by the roles of quiet eye and eye–head stabilization in successful performance.

Effects of skill and accuracy

Although the skilled and less skilled participants differed in their ability to produce accurate responses, we found no differences in quiet eye or eye–head stabilization as a result of skill or accuracy. For the high skill group, the periods of quiet eye and eye–head stabilization represented 34% and 10% of total flight time respectively; for the low skill participants, these figures were 36% and 9% respectively. Skill differences in quiet eye duration have been reported in a variety of gaze behaviour tasks, including billiards (Frehlich et al., 1998), basketball (Ripoll et al., 1986; Vickers, 1996), golf (Vickers, 1992) and volleyball (Vickers and Adolphe, 1997). The varying constraints imposed by the current task may provide an explanation for the unexpected results. In volleyball receiving, for example, the total ball flight duration is much longer (about 1470 ms) than in the present study (about 800 ms). The longer flight time in volleyball may have contributed to the less experienced players stepping to play the ball earlier before acquiring visual information relevant to their action.

It could be argued that the high skill participants in the current study were less skilled than those used by Ripoll and Fleurance (1988), Bootsma and van Wieringen (1990) and Vickers and Adolphe (1997). However, in the present study three participants were champions at provincial or national standard and the overall group accuracy scores were high. For example, in Bootsma and van Wieringen’s (1990) study, the players recorded 75% accuracy in hitting a circular target, with the ball delivered by a machine with the same speed and direction each time. In the present study, although the serves were slower, the participants had to hit two targets on opposite sides of the table, with the ball served in a random fashion by a human server. The average accuracy across all cue conditions was 52.9%. The accuracy scores for the high skill group in the pre-cue condition without eye tracker was 44.4–79.4%, with a mean of 61.3%. This range of scores is comparable with that reported by Bootsma and van Wieringen, even though the conditions of play in the current study were more challenging. Vickers (1996) and Vickers and Adolphe (1997) reported combined accuracies (experimental and game) of 78% and 63% respectively for their expert participants. Alternatively, the slightly faster ball velocities faced by the skilled players may have confounded the expected differences in quiet eye and eye–head stabilization. The serves to the high skilled participants were slightly faster (the mean difference in time from serve to second ball bounce, a value not affected by arm movement strategies, was approximately 35 ms). This difference, although small, may have altered gaze behaviour and contributed to the observed results.

Quiet eye onset was delayed for the low skill group during misses compared to hits. The amount of time taken by the low skill participants to start tracking appeared crucial for their success in hitting the target. When the less skilled participants initiated quiet eye after 24% of flight time, this typically resulted in a miss, whereas when it was initiated after around 18% of ball flight time, a hit was more likely. The high skill participants initiated quiet eye earlier than their low skill counterparts on hits (12%) and misses (10%), thereby taking advantage of early information acquisition. Although there were no significant differences in quiet eye duration and offset between skill groups, the results are in line with those of Land and McLeod (2000), who reported that high skill players were able to acquire the initial visual information faster and started their downward saccade towards the bounce area earlier. Vickers and Adolphe (1997) also showed that early onset of ball tracking is a characteristic of skill when receiving the serve in volleyball.

Skilled participants did not use higher arm velocities during the execution of the stroke as predicted. The high skill group appeared to preserve accuracy on the target, at the expense of lower arm velocities at contact. The control of arm deceleration in such circumstances could be related to the absence of skill differences in arm velocity at contact and movement time (see Teasdale and Schmidt, 1991). In future research, variables such as arm peak velocity, time to peak velocity and the ratio of the duration of the acceleration phase to the duration of the deceleration phase (Teasdale and Schmidt, 1991; Carnahan et al., 1993) may provide more detailed information on how distinct differences in skill control sport-related interceptive actions. The high and low skill participants did show higher arm velocities at contact during misses than hits. Participants who used higher arm velocities were more likely to miss the target, which can be explained by the principle of speed–accuracy trade-off (Fitts, 1954). Fitts’ law implies an inverse relationship between the difficulty of a movement and the speed with which it can be performed. This principle 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 (Schmidt and Lee, 1999).

Effects of cue condition

The effects of cue delay are observable in the plots of gaze relative to the ball (Figs 4A, 4C and 4E) and gaze in space (Figs 4B, 4D and 4F). In the pre-cue condition, the participants had ample time to detect the cue light, track the ball and move gaze to the correct side to receive the ball. In the early-cue condition, they changed their gaze behaviour and maintained their accuracy by making a fast shift of gaze to the ball. In the late-cue condition, they had to wait for the cue and performed much smaller gaze movements, with higher variability. Gaze stability occurred just before contact in all cue conditions. Effects of cue condition on arm movements were observed. A general reduction in arm movement amplitude (Figs 5A, 5C and 5E) and velocity (Figs 5B, 5D and 5F) was apparent as the cue was delayed.

In the pre-cue condition, the cue light was triggered approximately 1.6 s before the serve. Also, the participants had ball flight time, an average of 821 ms, to respond. During the early-cue condition, the cue was activated 263 ms after service contact, leaving a mean of 521 ms to organize and execute the movement response. In the late-cue condition, the cue was triggered 492 ms after the serve, leaving only 327 ms to complete the action. A significant decline in performance accuracy was observed in the late-cue condition (mean = 30%) compared with the pre- and early-cue conditions (combined mean = 48%). As arm movement was initiated approximately 160 ms before ball–bat contact in the late-cue condition, a duration of 167 ms (327 minus 160 ms) was left to process visual information regarding the cue, which approximates a well-documented difference in processing time. Visual simple reaction time in motor and other skills has a reported threshold between 150 and 180 ms, below which performance is degraded (Carlton, 1981a,b; Zelaznik et al., 1983).

The deterioration in performance in the late-cue condition was associated with the following changes (see Table 2). The duration of quiet eye was reduced from pre- to early-cue and from early- to late-cue conditions, but eye–head stabilization did not occur earlier as the cue was delayed. This finding indicates that visual information acquisition through quiet eye was disrupted by the presentation of cue lights and not compensated for by earlier eye–head stabilization. In the early- and late-cue conditions, the two main sources of information in the task (the ball and the cue) were concurrently available and spatially separated. No previous studies have used such a manipulation. Although the duration, onset and offset of eye–head stabilization were not substantially affected by cueing, it did occur in different locations (see Figs 4B, 4D and 4F); this allowed participants to maintain gaze closer to the cue lights during eye–head stabilization as the condition became more difficult. Gaze was far from the ball during eye–head stabilization and this distance increased very rapidly until contact (see Figs 4A, 4C and 4E). Quiet eye onset was similar in the pre- and early-cue conditions but occurred significantly earlier in the late-cue condition, implying that the participants tried to acquire information as early as possible to provide time to detect the cue light. Quiet eye offset occurred earlier as the cue presentation was delayed. Arm velocity at contact was also reduced from the pre- to early-cue conditions, but it did not differ between the early- and late-cue conditions. Interestingly, the participants did not alter movement time onset or duration as they did with arm velocity at contact to overcome the cueing manipulation. Movement time is traditionally assumed to be a parameter in the generalized motor program theory, a motor control feature that is easily adjustable, in contrast to other invariant aspects of the movement (Schmidt, 1985).

Functions of quiet eye and eye–head stabilization

The quiet eye and eye–head stabilization mechanisms helped to stabilize the ball’s image early in flight and the scene image immediately before ball–bat contact. Both quiet eye and eye–head stabilization were present in most trials in the pre- and early-cue conditions, but one or the other, especially eye–head stabilization, was absent in the late-cue condition (Table 1).

Vickers (1996) argued that ‘the duration of QE [quiet eye] plays a key role in the optimal organization of the neural structures underlying’ motor skills (p. 352). She 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). In this context, the present study asked the question: What are the consequences of delaying the information regarding one specific aspect of the required action (i.e. right or left direction of ball return)? In the pre-cue condition, the duration of quiet eye was about 400 ms (52% of ball flight duration), compared with 264 ms (33%) in the early-cue condition and 182 ms (22%) in the late-cue condition. 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 in gaze and arm behaviour and did not affect accuracy. A longer delay (late-cue) was problematic in terms of maintaining accuracy and generated several adaptations described previously.
How did quiet eye and eye–head stabilization provide visual information for controlling the stroke in table tennis? The mean quiet eye duration of 400 ms (pre-cue) used in this table tennis task was longer than that used in previous studies. For example, Ripoll and Fleurance (1988) showed that players visually tracked the ball for a mean of 150 ms during regular forehand drives and for 185 ms during forehand drives with top spin. Similarly, Land and McLeod (2000) found that cricketers tracked the ball for 150–200 ms before initiating an anticipatory saccade. However, Ripoll and Fleurance required players to partake in a continuous ‘rally’, whereas Land and McLeod used higher ball velocities, greater distances from the release point to the participant and greater angular distance from the position of ball delivery to ball–bat contact in their cricket task. In spite of the differences, these studies show that the quiet eye period is important in providing information on the ball’s trajectory and likely location of bounce and in planning the ensuing motor response (Vickers, 1996).

In the final part of ball flight, movement time was initiated approximately 160 ms before contact. As the arm moved towards the ball, eye–head stabilization was initiated, which lasted for about 100 ms, up until a point 30 ms before ball–bat contact. Ripoll and Fleurance (1988) reported an eye–head stabilization duration of 375 ms for regular forehand drives and 238 ms for forehand with top spin drives, while Land and McLeod (2000) showed that batsmen tracked the ball for up to 200 ms after the bounce. Ripoll and Fleurance (1988) suggested that eye–head stabilization may facilitate the extraction of information from the final portion of the ball’s flight using an ‘image–retina’ rather than an ‘eye–head’ system (see also Haywood, 1984). When using the eye–head system, a combination of eye and head movements is used to keep the ball stationary on the eye, as in the quiet eye period. In the image–retina system, the head and eyes are kept motionless as the ball moves across the retina, which increases sensitivity to ball motion through peripheral vision (Bruce and Green, 1990; Schwartz, 1994). The table tennis players in the present study did not use a final tracking of the ball as the cricketers did in the study of Land and McLeod (2000). It could be suggested that the cricketers tracked the final part of ball flight to monitor the ball’s bounce off the more unpredictable wicket and to allow changes in the stroke if necessary. Land and McLeod (2000) also proposed that other cues such as image expansion could refine estimates of time and position of contact already obtained.

The tau strategy hypothesis (Lee, 1976, 1980; Lee and Reddish, 1981; Lee et al., 1983; Yilmaz and Warren, 1995) proposes that the image expansion (from which time to contact information can be derived) supports visual timing of interceptive actions (for a discussion, see Wann, 1996; Tresilian, 1997). However, the role of eye movements is not clearly defined in this perspective (see Warren and Hannon, 1990; Cutting, 1996; Kim et al., 1996a,b). An aspect relevant to the present discussion is that, when the velocity of approach is increasing, the optic variable tau overestimates the actual time to contact, but they converge just before contact, showing the importance of gaze behaviour around this time. For example, consider the convergence observed during the final 250–300 ms before hitting a falling ball under gravitational acceleration (Lee et al., 1983) and the final 150 ms when blocking a karate kick (Rodrigues et al., 1994). Land and McLeod (2000) argued that, given the accuracy required, it would be difficult for cricket batsmen to rely on the ball’s image size and its rate of expansion due to the very small magnitudes during its initial flight. However, as the rate of expansion increases very rapidly through ball flight, tau would be an accurate estimate of time to contact during eye–head stabilization, and it would contribute to refinements and late arm adjustments in the present study.

An interesting issue is whether the information available in the final part of ball flight, captured during eye–head stabilization, can be effectively used to alter or adjust arm action. Controversy exists as to whether vision can guide action faster than visual reaction time. Visuo–motor delays (the processing delay between the acquisition of visual information and its use in motor responses) of 55–130 ms (Lee et al., 1983) and 105–156 ms (Bootsma and van Wieringen, 1990) have been reported. Milner and Goodale (1995) proposed that visual information is processed through the dorsal stream during the control of goal-directed actions, whereas the ventral stream is responsible for object identification and discrimination; two visual systems with distinct processing speeds. Goodale and Haffenden (1998) also argued that the dorsal stream relies heavily on input via peripheral vision, whereas the ventral stream is more closely associated with central vision. The dorsal or ‘vision-for-action’ system is thought to support movement adjustments shorter than 100 ms. Milner and Goodale’s model, which has recently been debated among ecological psychologists (e.g. Michaels, 2000; van der Kamp et al., 2001), can accommodate evidence from both early information acquisition to predict a ball’s future trajectory and action planning, and late movement adjustments based on image expansion information. Further research is necessary to clarify how the two visual systems cooperate during eye, head and arm movement initiation (Rodrigues et al., 1999).

In this study, the manipulation of cue onset time showed the limits of adaptation to maintain spatial
accuracy on the target. When participants had approximately 520 ms to identify the cue and respond in the early-cue condition, accuracy was maintained compared to when the cue was seen before the serve (pre-cue). To accommodate the spatial and temporal constraints presented in the early-cue condition, the participants reduced the duration of quiet eye, terminated quiet eye earlier and recorded lower arm velocities during stroke execution. When the participants had approximately 320 ms to detect the cue and act (late-cue), 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, as an attempt to preserve accuracy. In addition, the participants were less able to keep both the ball image stable during the preparation phase and gaze stable during the execution phase of arm action. No expertise advantage was found in gaze and arm movements, even in the late-cue condition. The high skill participants responded more accurately under extreme temporal constraints, but their superiority was not reflected in the variables accessed in this study. In this study, a novel method was used to enable the concurrent assessment of three-dimensional kinematics of the ball, line of gaze and arm in a natural, sport-specific context. This method provides a potentially fruitful approach when examining the complex relationship between vision and action in sport and other contexts.

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References


