Gaze pursuit and arm control of adolescent males diagnosed with attention deficit hyperactivity disorder (ADHD) and normal controls: evidence of a dissociation in processing visual information of short and long duration

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Three-dimensional kinematic analysis of line of gaze, arm and ball was used to describe the visual and motor behaviour of male adolescents diagnosed with attention deficit hyperactivity disorder (ADHD). The ADHD participants were tested when both on (ADHD-On) and off (ADHD-Off) their medication and compared to age-matched normal controls in a modified table tennis task that required tracking the ball and hitting to cued right and left targets. Long-duration information was provided by a pre-cue, in which the target was illuminated approximately 2 s before the serve, and short-duration information by an early-cue illuminated about 350 ms after the serve, leaving ~500 ms to select the target and perform the action. The ADHD groups differed significantly from the control group in both the pre-cue and early-cue conditions in being less accurate, in having a later onset and duration of pursuit, and a higher frequency of gaze on and off the ball. The use of medication significantly reduced the gaze frequency of the ADHD participants, but surprisingly this did not lead to an increase in pursuit, suggesting a barrier was reached beyond which ball flight information could not be processed. The control and ADHD groups did not differ in arm movement onset, duration and velocity in the short-duration early-cue condition; in the long-duration pre-cue condition, however, the ADHD group's movement time onset and arm velocity differed significantly from controls. The results show that the ADHD groups were able to process short-duration information without experiencing adverse effects on their motor behaviour; however, long-duration information contributed to irregular movement control.

Keywords: eye movements, methylphenidate, motor coordination, pursuit tracking.

Introduction

Attention deficit hyperactivity disorder (ADHD) is usually characterized by a persistent pattern of inattention and/or hyperactivity–impulsivity (American Psychiatric Association, 2000). Children, adolescents and adults diagnosed with primary attention deficit (ADHD-PI) cannot sustain attention on relevant objects and events in their environment, while those with primary hyperactivity (ADHD-H) show inordinately high impulsiveness in motor behaviour. Those diagnosed with combined deficit (ADHD-C) exhibit deficits of both attention and hyperactivity. Attention deficit hyperactivity disorder affects approximately 4–6% of all children, with estimates varying from 1.7 to 17% worldwide (Elia et al., 1999; Farone et al., 2000; Zametkin and Ernst, 1999). It is more widespread in males than females during both childhood and adolescence by a ratio of 4:1 and in adulthood by a ratio of 2:1. The persistence of ADHD into adulthood has been estimated to be as high as 80% (Farone et al., 2000).

There is currently no objective test for diagnosing the condition and there is no universally recognized treatment (Barkley, 1998; Elia et al., 1999). Attention
deficit hyperactivity disorder is treated using psycho-stimulant medication such as methylphenidate (Ritalin), dextroamphetamine (Dexedrine) or related drugs, which have been described as ‘well-established safe drugs for patients with this disorder and are the treatments of choice’ (Elia et al., 1999, p. 780). Although medication has been shown to reduce impulsive behaviour and improve school performance in the short term, long-term gains in academic or motor performance have not been reported (Losier et al., 1996; Elia et al., 1999).

As the number of children, adolescents and adults diagnosed with ADHD increases (Safer et al., 1996; Elia et al. 1999; Farone et al., 2000; Zametkin and Ernst, 1999), extensive efforts have been devoted to defining the core or primary deficit of the disorder (Barkley, 1998; Douglas, 1999). From the 1930s to 1960s, ADHD was attributed to ‘minimal brain damage’, ‘minimal brain dysfunction’, ‘hyperkinesis’ and ‘hyperactivity’ (Barkley, 1998). By the mid-1970s, a growing body of evidence suggested that the root of the disorder was a deficit in attention (Douglas, 1972; Douglas and Peters, 1979). The core disorder was defined in the 1980s and focused on the cognitive-behavioural areas of inattention and impulsivity, rather than the harder-to-define and less specific motor manifestations. Excessive motor activity was viewed as problematic, but not central to the disorder (Jellinek and Herzog, 2000). Consequently, the motor aspects of the disorder have not been researched extensively; the problem of perception-action coupling has not been investigated to any great extent in ADHD either.

Douglas (1999) presents a defective regulatory control hypothesis as an inclusive framework within which the attention, inhibitory and processing problems of ADHD can be integrated. She defines inhibitory deficits as those related to being unable to maintain performance across time, adjust readiness to respond to designated stimuli, shift responses flexibly to meet task demands, as well as the ability to change response speed on demand and inhibit responding to inappropriate stimuli. As evidence, she shows that individuals with ADHD find long-duration tasks more difficult than those of short duration, and have particular difficulty in tasks with long preparation intervals, long delays between cue presentation and target onset (Swanson et al., 1991) and long pre-response delays (Sonuga-Barke and Taylor, 1991). Others have found that children with ADHD have great difficulty projecting forward in time, cannot anticipate the next decision or movement, and are unable to accurately reproduce the duration of time intervals (Barkley, 1998; Woods and Ploof, 1997). Tannock (in Paule et al., 2000) describes two timing systems related to ADHD, one that operates in the millisecond or short-duration range controlled relatively automatically by subconscious processes, and a second, long-duration system that requires sustained attention, the use of short-term memory and other cognitive processes, such as memory and strategic thinking. Behavioural timing in the millisecond range may be achieved relatively automatically through an internal timing system, whereas the processing of longer-duration information is more problematic in ADHD. Short-duration task information varies across studies and falls roughly in the 200–500 ms range, whereas information of long duration exceeds this range. Across studies, the regulation of time has emerged as a possible core deficit of ADHD.

**Evidence of a dissociation in processing long- and short-lived task information**

Modern conceptions of normal sensory motor processing present accumulating evidence of a dissociation between two visuo-motor systems (Cohen and Squire, 1980; Ungerleider and Mishkin, 1982; Shachter, 1987; Bridgemen et al., 1991; Ripoll, 1991; Bridgeman, 1992; Milner and Goodale, 1995; Rossetti, 1998; Tannock, in Paule et al., 2000). In an attempt to reduce the confusion of so many competing models, Rossetti (1998) provides evidence that processing time plays a critical role in many of the dual models of sensori-motor control proposed to date. Healthy individuals are able to move their hands precisely to objects in short-duration tasks, even under conditions of darkness or object movement that coincides with saccades, but when delays are allowed their performance is impaired (Goodale et al., 1986; Pelisson et al., 1986; Rossetti et al., 1995). When brain-injured patients are given ample time to perform a skill, information presented early appears to ‘contaminate’ their behaviour, whereas that presented late, or not at all, does not create the same amount of perturbance (Perinin and Rossetti, 1996; Rossetti, 1998). The short-duration frame of reference appears to be spared in patients who have lost conscious perception of visual, tactile or proprioceptive stimuli. Observation of these patients shows that they are attracted to goals that require an immediate response and where no cognitive representation of the goal is elaborated upon at the same time. In normal motor behaviour, it appears that ‘immediate action is not mediated by the same system as delayed action . . . action can be controlled by a sensory system which is specialised for on-line processing of relevant goal characteristics. The temporal constraints of this system are such that it can affect the action before any sensory analysis of this goal has been completed’ (Rossetti, 1998, p. 520). During normal motor behaviour, the short- and long-duration visuo-motor systems function
in an integrated manner so that task information is passed from one to the other in a way that results in smooth and coordinated action. How these systems function to produce coordinated behaviours is a topic of considerable debate.

We hypothesized that a deficit may exist in patients with ADHD, such that long-duration visual information is either impeded or ‘contaminated’, while short-duration information is processed in a normal, albeit limited manner, relative to that which occurs when both systems function normally. To explore this problem, individuals with ADHD were tested when both on (ADHD-On) and off their medication (ADHD-Off) and compared to age-matched normal controls in a modified table tennis task used in previous studies with high and low skilled adults (Rodrigues et al., 1999, this issue). Long- and short-duration task information was provided by two temporally distinct cues. In the pre-cue condition, the cue light was illuminated before the service; in the early-cue condition, the cue light was illuminated after the serve, leaving approximately 500 ms to organize and perform the hitting action. In both conditions, long-duration information was provided by the flight of the ball, which averaged approximately 850 ms across trials and conditions.

Besides being an ecologically valid task, table tennis is a skill that has been researched extensively in terms of describing normal gaze and arm control of both novice and highly skilled players (Bootsma, 1988; Ripoll and Fleurance, 1988; Bootsma and van Wieringen, 1990; Rodrigues, 2000; Rodrigues et al., this issue). In the following sub-sections, we first review the available literature on the gaze and arm control of normal individuals in table tennis, then review relevant studies of ADHD eye movements and motor coordination.

Gaze control in table tennis
Studies of table tennis (Ripoll and Fleurance, 1988; Rodrigues and Vickers, 1998; Rodrigues et al., 1999, this issue) and related skills (Bahill and LaRitz, 1984; Vickers and Adolphe, 1997) have found that both novice and elite performers begin tracking the ball immediately and maintain tracking over 50–60% of early ball flight. Pursuit tracking rarely occurs during the latter part of ball flight; instead, the gaze is maintained in a stable position in advance of the ball as it is hit. Since it is normal for the eyes to deviate on and off the ball during flight (Bahill and LaRitz, 1984; Ripoll and Fleurance, 1988; Vickers and Adolphe, 1997), the final period of sustained tracking on the ball has been termed the ‘quiet eye’ period (see Vickers, 1996; Rodrigues et al., this issue). Quiet eye occurs when the ball is foveated within 3° of visual angle for a minimum of 100 ms; therefore, information about ball speed and direction is available for processing and used in organizing and executing the arm action. Since smooth pursuit tracking is dependent on ‘an internal estimate or prediction of what the movement of the target is in space . . . that is more closely related to the perceived target time than its actual time’ (Carpenter, 1988, pp. 56–57), the quiet eye period is the moment before the execution of the movement when visual attention may be most focused. The quiet eye period has been found in a range of motor skills and skilled performers have been shown to have an earlier quiet eye onset and/or a longer duration than less skilled individuals (Vickers, 1996; Rodrigues and Vickers, 1998; Rodrigues et al., 1999, this issue; Frehlich et al., 1999; Janelle et al., 2000a,b; Harle and Vickers, 2001; Williams et al., in press).

Arm control in table tennis
Arm control in table tennis has been described by Bootsma (1988), Bootsma and van Wieringen (1990) and Rodrigues et al. (this issue), with special attention paid to when the forward arm movement is initiated (movement time onset), the duration of the movement and arm velocity at contact. Results are similar across studies and show that movement time duration, whether for elite players (139 ± 11.7 ms; mean ± s), high skilled players (150 ± 47.6 ms) or low skilled players (165 ± 52.2 ms), are very similar, whereas complete novices have slightly longer movement times (239 ± 38.3 ms). Rodrigues et al. (this issue) found that arm velocity at contact did not differ between high (91.6 ± 33.7 cm·s⁻¹) and low skilled players (89.8 ± 36.7 cm·s⁻¹) when expressed as a linear measure. Movement time onset also did not differ, with elite, high and low skilled players initiating the forward movement of the arm after 79.0%, 76.0% and 77.0% of ball flight, respectively. Among normal adults, the available evidence shows that the onset and duration of movement time, as well as arm velocity at contact, are largely unaffected by skill or accuracy.

Perception–action coupling in table tennis
Since there is no single measure of arm control that differentiates skill and accuracy in table tennis, Bootsma (1988) and Bootsma and van Wieringen (1990) explored the coupling of perception and action using the optic variable tau (Lee, 1976). Correlations between the perceptually specified time-to-contact tau–margin at onset of the swing (defined as ‘the inverse of relative dilation of the closed optical contour generated in the optic array by the approaching object’; Bootsma, 1988, p. 115) and mean bat velocity and acceleration were used to estimate the coupling between perception and action. Significant correlations were found for
high skilled individuals, with a positive correlation indicating low trial-to-trial variability and evidence of pre-programming, while a negative correlation indicated adjustments were made during the arm movement using visual guidance.

As in the present study we investigated the gaze and arm control of a younger and more inexperienced group of participants, it was not as important to detect a positive or negative correlation as to find a correlation between the gaze and arm variables in the first instance. Unlike Bootsma, who could only estimate the coupling of perception and action using tau, we had precise measures of when and for how long the ball was tracked (onset, offset and duration of quiet eye) and measures of arm control (onset and duration of movement time, arm velocity at contact). The absence of any correlation between these arm and gaze control variables would indicate abnormal perception–action coupling and a possible dissociation between the gaze system responsible for tracking the ball and motor system responsible for control of the arm.

**Eye movements and motor coordination in ADHD**

Children and adolescents with ADHD have been shown to differ from age-matched controls in both saccadic (Ross et al., 1993, 1994) and pursuit tracking eye movements (Jacobsen et al., 1996). Ross et al. (1993) used an oculo-motor delayed response task to cue individuals to where they should look, but delay for a short period, and then shift the gaze to the location where the cue previously but no longer existed (a memory-guided saccade). Compared to controls, the ADHD participants were unable to inhibit saccades during the delay period, but looked to the target sooner than controls, leading Ross and colleagues to suggest that the primary deficit was an inability to inhibit saccades. Jacobsen et al. (1996) found that adolescents with ADHD were unable to maintain continuous tracking on a moving stimulus with a constant velocity of 0.19 rad·s⁻¹. The ADHD participants had a root mean square error of 2.9°, compared with 1.9° for controls, indicating they had difficulty sustaining tracking over time. The available evidence, therefore, shows that ADHD patients have a deficit in tracking and saccadic eye movements; however, it is unclear whether the underlying cause is a deficit in saccadic inhibition or reasons related to being unable to process long-duration task information, which, in turn, may be the impetus for more saccadic eye movements.

Individuals with ADHD perform more poorly in motor skills than normals; however, the underlying reasons for their poorer motor coordination are unknown (Piek et al., 1999; Gillberg and Kadesjo, 2000). Piek et al. (1999) compared boys with ADHD-PI/C and boys matched on age and verbal IQ on measures of motor coordination and found that the ADHD children had significantly poorer movement abilities than controls. The severity of the children's inattention was reported to be a significant predictor of their motor coordination difficulties. Gillberg and Kadesjo (2000) found that most children who had ADHD also had symptoms consistent with developmental coordination disorder.

Measures of arm and gaze control were therefore determined for ADHD-On, ADHD-Off and normal control groups. The primary focus was on the effect of the long- and short-duration cues on accuracy (%), gaze frequency, the onset, offset and duration of quiet eye, the onset and duration of movement time, and arm velocity at contact. Based on previous research, we expected that, relative to the control group, the ADHD groups would have difficulty maintaining gaze on the ball, which would be indicated by a higher gaze frequency, a later quiet eye onset and a shorter quiet eye duration. Low or no correlation was expected between the gaze (onset and duration of quiet eye) and arm control variables (onset and duration of movement time, arm velocity at contact) of the ADHD groups, while it was expected the controls would exhibit correlations similar to those found in previous research. In addition, a condition effect was expected, with the long-duration pre-cue creating a greater disturbance in the gaze and arm control of the ADHD groups than the early-cue. We also expected the use of medication to have no detrimental effects on the accuracy, gaze or arm control of the ADHD-On group.

**Methods**

**Participants**

The ADHD participants were recruited using an advertisement in a local newspaper. Forty-three individuals responded and eight males were selected after a screening interview using Barkley and Murphy's (1998) ADHD Clinical Questionnaire adapted for adolescents, and confirmation by their physician and/or psychologist of an ADHD-PI or ADHD-C diagnosis. The ADHD participants were age-matched with seven normal controls and both groups were screened for learning disabilities, anxiety disorders, reading disabilities and the use of other medications. All were right-handed; none played table tennis competitively, although three of the control group played competitive badminton. The ADHD group was tested on two occasions, while on medication and off it for a minimum of 48 h. (Note: two of the ADHD participants had been off medication for an extended period.) To minimize order effects, half of the ADHD participants were tested when on their...
medication followed by being off their medication; the reverse procedure was used for the other half. Six of the ADHD participants were taking Ritalin and two Dexedrine (24.4 ± 6.20 mg).

Ethics approval was received before testing. The participants and their guardians or parents signed an informed consent and the participants received a small honorarium at the end of testing. The participants’ ages, ADHD diagnoses and medications are summarized in Table 1.

### Table 1. Age, diagnosis and medication status of ADHD (On and Off) participants and controls

<table>
<thead>
<tr>
<th>Group</th>
<th>ADHD</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of participants</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Age (years)</td>
<td>mean</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>standard deviation</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>range</td>
<td>13–16</td>
</tr>
<tr>
<td>Diagnosis</td>
<td>ADHD-PI</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>ADHD-C</td>
<td>3</td>
</tr>
<tr>
<td>Medication at testing</td>
<td>Ritalin</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Dexedrine</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>none</td>
<td>7</td>
</tr>
</tbody>
</table>

**Apparatus**

**Vision-in-action system**. The vision-in-action system (Vickers, 1996) integrated a mobile eye tracker with an external camera that assessed the participants’ eye and body movements, a time code generator and two video mixers that coupled the participants’ gaze, motor and ocular behaviours. An Applied Sciences Laboratories 501 Eye Tracker (accuracy of ±1° of visual angle and precision of 0.5°) 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 (A), 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 infrared light source. The top portion of the frame (B) was 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 (C) 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), which provided 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. The 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 (coinciding with ball trajectory) was performed before each trial. For more information, see Rodrigues (2000).

Experimental task. Figure 2 shows a regulation table tennis table fitted with cue lights, server and participant, as well the location of the eye tracker, magnetic head tracker, six cameras of the motion analysis system, an external camera and laser net device; this was similar to that used by Rodrigues et al. (this issue). The task set-up required the return of a table tennis ball to either the left or right side of the table using a forehand drive. The server was a highly skilled player who delivered the ball at a moderate speed to a 40 × 60 cm oval chalked on the table, denoting the location of the second bounce. The 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. In the long-duration pre-cue condition, the target cue came on approximately 2 s before the serve; in the short-duration early-cue condition, the target cue came on about 350 ms after the ball was served and passed through the laser net, randomly triggering the right or left cue lights. The pattern of ball flight was quite consistent, although

Fig. 2. View of the table tennis table showing the participant, server, flight of the ball during the serve delivery and target areas. The eye tracker, magnetic head tracker, motion analysis system with six cameras, external camera, laser device, and right and left cue lights are also illustrated.
the analysis revealed that slightly faster serves were delivered to the controls. For the controls, the second ball bounce occurred earlier (595 ± 30.8 ms; \(F_{1,80} = 4.49, P < 0.02\)) and total ball flight was faster (819 ± 5.78 ms; \(F_{1,80} = 5.79, P < 0.01\)) than for the ADHD-On (second bounce = 635 ± 34.0 ms; total flight time = 908 ± 61.8 ms) and the ADHD-Off (second bounce = 627 ± 41.2 ms; total flight time = 907 ± 90.2 ms) groups.

Data acquisition protocol

The participants were fitted with retroreflective markers attached to the elbow (head of radius) and wrist (ulnar head) of the right hand to allow the digital processing of marker recognition. After 15 min of instruction and warm-up with the server, they were tested without the eye tracker for accuracy in counterbalanced pre-cue and early-cue conditions. They were then fitted with the eye tracker, calibrated and performed practice trials to ensure comfort of the eye tracker. This was followed by the completion of counterbalanced pre-cue and early-cue conditions. In each condition, consecutive trials were performed until five hits and five misses were achieved or 20 trials, whichever came first. The time taken to complete the test was 60 min. A one-way analysis of variance was used to examine the effect of wearing the eye tracker (with, without) and percentage of hits by condition (pre-cue, early-cue). Separate tracker (without, with) × condition (pre-cue, early-cue) analyses of variance, with repeated measures on both factors, showed that wearing the eye tracker did not affect the performance of the controls (\(F_{1,6} = 0.10, P < 0.76\)), ADHD-On (\(F_{1,7} = 0.23, P < 0.65\)) or ADHD-Off (\(F_{1,7} = 1.18, P < 0.32\)) groups. The accuracy of the control group without and with the eye tracker was 45.5 ± 16.0% and 47.3 ± 11.0% respectively. For the ADHD-Off group, the respective figures were 28.6 ± 12.0% and 23.8 ± 15.0%; for the ADHD-On group, they were 30.5 ± 17.0% and 28.6 ± 11.0% respectively.

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 the ball that was smoothed at 30 Hz. To transform the eye–head integration data from 60 to 180 Hz, linear interpolation was used for gaze data because of 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 Rodrigues, 2000; Rodrigues et al., this issue): the visual angle between line of gaze and ball edge; visual angle between line of gaze and the x-axis of the transmitter coordinate system; and the angle between arm (segment from elbow to wrist) and the x-axis of the transmitter coordinate system. 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); each point in time represented a proportion of the total time (Schmidt and Lee, 1999).

Dependent variables

The dependent variables are shown in Fig. 3. Each trial began when the ball was served (0% relative time) and ended when hit by the participant (100%). Quiet eye was the final pursuit tracking on the ball; quiet eye onset occurred before the initiation of the forward arm action and quiet eye offset occurred when the gaze deviated off...
the ball edge more than 3° of visual angle for a minimum of 100 ms (limits derived from Ripoll and Fleurance, 1988; Vickers and Adolphe, 1997; Helsen et al., 1997). The duration of quiet eye was calculated as quiet eye offset minus quiet eye onset. Tracking during movement time was a measure of pursuit tracking that occurred during movement time and was determined in a manner similar to quiet eye. No analyses were performed on tracking during movement time because of the low incidence of this gaze, a result similar to that reported by Rodrigues et al. (this issue). Gaze frequency was a measure of gaze-ball angle deviations during the flight of the ball, from serve to contact. A gaze frequency of 1 was recorded when the gaze deviated more than 3° of visual angle on or off the ball. Movement time was defined as the forward movement of the arm (a definition similar to that used by Bootsma, 1988; Ripoll and Fleurance, 1988; Bootsma and van Wieringen, 1990; Rodrigues, 2000; Rodrigues et al., this issue). The movement time onset criterion was the greatest angle between the arm (elbow-wrist segment) and x-axis of the head tracker transmitter coordinate system (the coordinate system in which all angular variables were measured after transformations). This period was characterized by a decrease in angular position of the arm movement. Movement time offset occurred at ball-bat contact. Contact was defined as the last data point before the ball exhibited a change in direction, obtained from the three-dimensional coordinates of the ball. Movement time duration was calculated as movement time offset minus movement time onset. Arm velocity at contact (cm·s⁻¹) was the instantaneous linear velocity of the wrist marker at the time of contact, and was calculated as the change in position from the data point immediately before contact to the data point immediately after contact, divided by the time elapsed (Winter, 1990).

**Pursuit tracking on the ball of ADHD-Off, ADHD-On and control groups**

The pursuit tracking of the participants was plotted on all trials. Figure 4 presents the pursuit tracking of three

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Fig. 4. Pursuit tracking of three ADHD and three control participants in the pre-cue condition. Plots are shown for the ADHD participants when off and on medication. The y-axis shows the visual angle (degrees) of the gaze from the ball edge. The 3° threshold is indicated by the horizontal dotted line. Relative trial time is shown on the x-axis, from 0% (service of the ball) to 100% (ball-bat contact).
controls (S11, S13, S18) and three ADHD individuals (S4, S9, S15) in all trials of the pre-cue condition. The gaze of the ADHD participants is shown first off and then on medication. The y-axis shows the gaze relative to the ball edge in degrees of visual angle. The x-axis shows the flight duration of the ball with 0% coinciding with the serve and 100% ball–bat contact. The horizontal dotted line denotes the 3° threshold used for defining quiet eye tracking.

The plots of the three controls are very similar to those reported by Rodrigues et al. (this issue) for high and low skilled adults. Pursuit tracking began immediately after the ball was served and was maintained within 3° of visual angle during early and mid ball flight. As the ball neared, the gaze deviated off the ball and tracking did not occur to contact. Instead, the gaze was maintained in advance of the ball and remained stable in a period of eye–head stabilization as the ball was struck. A lower gaze frequency is evident for the controls over the course of the ball flight compared to the ADHD-Off group.

The three ADHD-Off participants had greater difficulty tracking the ball, exhibiting a higher gaze frequency and a shorter duration of pursuit tracking. The use of medication (ADHD-On) appeared to have a quieting effect on the gaze, with a lower gaze frequency evident when on medication than when off. Individual differences are apparent in pursuit tracking in Fig. 4, with ADHD S9 having greater difficulty maintaining tracking on the ball when off medication than did S4 or S15. When on medication, S9 appeared to experience a greater relative benefit than S4 or S15.

Statistical analyses

The percentage of accurate returns to the designated target area (hits) was calculated with respect to the total number of trials in each condition. The movement time, quiet eye and arm velocity at contact data were derived from the first five hits in each condition and five misses randomly selected from the total of 20 trials per condition. Data were missing for three reasons: equipment malfunction, the participant was unable to complete five hits in the number allocated or a gaze behaviour was not used in a trial. Table 2 summarizes the missing data by group and cause of missing data. The data were analysed using analyses of variance with missing cells, as well as with the missing cells filled using mean values by group × condition × accuracy × trials. Since the results were similar, the analyses of variance with means are presented. Because of the between and within nature of the study, the control group was compared with the ADHD-Off group using a group (control, ADHD-Off) × condition (pre-cue, early-cue) × accuracy (hits, misses) × trials (1–5) analysis of variance, with repeated measures on the last three factors. A similar procedure was used to compare the control and ADHD-On groups. The ADHD-Off and ADHD-On groups were compared using a group (ADHD-Off, ADHD-On) × condition (pre-cue, early-cue) × accuracy (hits, misses) × trials (1–5) analysis of variance with repeated measures on all factors. Spearmen rho analysis was used to determine the correlation between the gaze (onset and duration of quiet eye) and arm variables (onset and duration of movement time, arm velocity at contact). 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 control group was significantly more accurate (F_{1,11} = 17.2, P < 0.001) than the ADHD-Off group. The accuracy of the controls was 46.4 ± 13.9% and that of the ADHD-Off group 26.2 ± 13.3%. Controls were significantly more accurate (F_{1,13} = 9.19, P < 0.009) than the ADHD-On group, which had an accuracy of 29.5 ± 14.2%. No significant differences were found between the ADHD-Off and ADHD-On groups. All three groups maintained similar accuracy in the pre-cue and early-cue conditions, a result also found by Rodrigues et al. (this issue) for high and low skilled adults. Table 3 summarizes the group means for accuracy, together with the means for gaze frequency, onset, offset and duration of quiet eye, onset and duration of movement time, and arm velocity at contact for the three groups.

Controls versus ADHD-Off group. When the controls were compared with the ADHD-Off group, a significant difference was found for gaze frequency (F_{1,52} = 14.4, P < 0.002) and quiet eye duration (F_{1,52} = 4.91, P < 0.04). Gaze frequency for the controls was significantly lower than for the ADHD-Off group, averaging 2.34 and 3.83, respectively. Quiet eye duration was significantly longer for controls (49.4%) than for the

<table>
<thead>
<tr>
<th>Table 2. Percent of missing data by group and cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>Equipment failure</td>
</tr>
<tr>
<td>Unable to complete hits</td>
</tr>
<tr>
<td>Gaze not present</td>
</tr>
</tbody>
</table>

ADHD gaze and arm control
ADHD-Off group (38.9%). Significant condition effects were found for gaze frequency, duration and onset of quiet eye; these were similar to those found by Rodrigues et al. (this issue) for normal adults. The early-cue caused gaze frequency to be higher, quiet eye onset to occur later and quiet eye duration to be longer. The interaction of condition x group was significant for movement time onset ($F_{1,52} = 5.37, P < 0.04$) and approached significance for movement time duration ($F_{1,52} = 4.23, P < 0.06$) and arm velocity at contact ($F_{1,52} = 3.89, P < 0.07$). In the early-cue condition, movement time onset for the ADHD-Off group (73.9 ± 8.66%) was similar to that for the controls (74.9 ± 8.66%), but it differed significantly in the pre-cue condition (controls 71.9 ± 3.63%, ADHD-Off 75.6 ± 8.29%), indicating that the ADHD-Off group was late in responding to the ball in the long-duration condition.

**Table 3.** Accuracy, gaze and arm control of the control, ADHD-Off and ADHD-On groups (mean ± s)

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>ADHD-Off</th>
<th>ADHD-On</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (%)</td>
<td>46.4 ± 13.9$^{d/e}$</td>
<td>26.2 ± 13.3$^{d}$</td>
<td>29.5 ± 14.2$^{d}$</td>
</tr>
<tr>
<td>Gaze frequency$^{a}$</td>
<td>2.34 ± 1.48$^{d/e}$</td>
<td>3.83 ± 1.89$^{d/e}$</td>
<td>2.80 ± 1.66$^{d/e}$</td>
</tr>
<tr>
<td>Quiet eye onset$^{b}$</td>
<td>14.4 ± 14.7$^{d}$</td>
<td>20.7 ± 19.0$^{d}$</td>
<td>23.2 ± 20.5$^{d}$</td>
</tr>
<tr>
<td>Quiet eye duration$^{b}$</td>
<td>49.4 ± 19.6$^{d/e}$</td>
<td>38.9 ± 18.7$^{d/e}$</td>
<td>37.0 ± 19.8$^{d/e}$</td>
</tr>
<tr>
<td>Quiet eye offset$^{b}$</td>
<td>63.9 ± 16.4</td>
<td>59.1 ± 19.7</td>
<td>60.5 ± 21.9</td>
</tr>
<tr>
<td>Movement time onset$^{b}$</td>
<td>73.4 ± 5.32</td>
<td>74.8 ± 8.49</td>
<td>72.2 ± 6.54</td>
</tr>
<tr>
<td>Movement time duration$^{b}$</td>
<td>26.6 ± 5.32</td>
<td>25.6 ± 8.41</td>
<td>27.3 ± 6.54</td>
</tr>
<tr>
<td>Arm velocity at contact (AVC)$^{c}$</td>
<td>50.6 ± 19.5</td>
<td>46.3 ± 14.9</td>
<td>52.6 ± 15.7</td>
</tr>
<tr>
<td>AVC condition x group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre-cue</td>
<td>50.5 ± 17.1</td>
<td>42.3 ± 12.0$^{f}$</td>
<td>55.2 ± 18.1$^{f}$</td>
</tr>
<tr>
<td>early-cue</td>
<td>50.7 ± 21.8</td>
<td>50.3 ± 16.4</td>
<td>50.1 ± 12.4</td>
</tr>
</tbody>
</table>

$^{a}$ Frequency of gaze deviating to or from the ball edge > 3° visual angle.
$^{b}$ Relative time – percent of total trial time (0% = ball serve; 100% = ball–bat contact).
$^{c}$ Arm velocity at contact in cm · s$^{-1}$.
$^{d}$ Controls differed significantly from ADHD-Off group.
$^{e}$ Controls differed significantly from ADHD-On group.
$^{f}$ ADHD-On group differed significantly from ADHD-Off group.

**ADHD-Off versus ADHD-On group.** Significant group differences were found for gaze frequency ($F_{1,28} = 5.32, P < 0.05$) and accuracy ($F_{1,28} = 5.34, P < 0.05$). Mean gaze frequency of the ADHD-On group was lower (2.80) than that of the ADHD-Off group (3.83). On hits, the gaze frequency of both ADHD groups was higher (3.53) than on misses (3.09). Significant condition effects were found for gaze frequency and quiet eye duration, similar to those found by Rodrigues et al. (this issue) for normal adults. The early-cue caused gaze frequency to be higher and quiet eye duration to be longer. The interaction of condition and group was significant for arm velocity at contact ($F_{1,28} = 16.8, P < 0.005$). Arm velocity of the ADHD-On and ADHD-Off groups was similar in the short-duration early-cue condition, exhibiting the invariance typically found in normal motor control (Bootsmaden and van Wieringen, 1990; Schmidt and Lee, 1999). However, in the long-duration pre-cue condition, the ADHD-On and ADHD-Off groups had significantly different arm velocities at contact. When on medication, they tended to over-hit the ball and when off medication to under-hit it. Figure 5 shows the arm velocities of the ADHD-Off and ADHD-On groups in the pre-cue and early-cue conditions. That of the controls is also shown for comparison purposes.
Table 4. Spearman rho correlations ($r_s$) between gaze (onset and duration of quiet eye) and arm movement variables (onset and duration of movement time, arm velocity at contact) of the ADHD groups combined and the controls in the pre-cue and early-cue conditions

<table>
<thead>
<tr>
<th></th>
<th>Pre-cue</th>
<th>Early-cue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>ADHD</td>
</tr>
<tr>
<td>QE onset, MT onset</td>
<td>$r_s = 0.27$, $P = 0.03$</td>
<td>$r_s = -0.06$, $P = 0.38$</td>
</tr>
<tr>
<td>QE onset, MT duration</td>
<td>$r_s = -0.27$, $P = 0.03$</td>
<td>$r_s = 0.09$, $P = 0.28$</td>
</tr>
<tr>
<td>QE duration, MT onset</td>
<td>$r_s = -0.29$, $P = 0.01$</td>
<td>$r_s = -0.10$, $P = 0.20$</td>
</tr>
<tr>
<td>QE duration, MT duration</td>
<td>$r_s = 0.29$, $P = 0.01$</td>
<td>$r_s = 0.10$, $P = 0.21$</td>
</tr>
<tr>
<td>MT onset, AVC</td>
<td>$r_s = -0.41$, $P = 0.0005$</td>
<td>$r_s = -0.07$, $P = 0.32$</td>
</tr>
<tr>
<td>MT duration, AVC</td>
<td>$r_s = 0.42$, $P = 0.0005$</td>
<td>$r_s = 0.06$, $P = 0.45$</td>
</tr>
</tbody>
</table>

Abbreviations: QE = quiet eye, MT = movement time, AVC = arm velocity at contact.

Discussion

This study was the first to examine how normal adolescents, as well as those diagnosed with attention deficit hyperactivity disorder (ADHD), acquire visual information through the movement of the head and eyes and carry out a complex manual aiming skill. Gaze and arm behaviours were examined during the execution of a table tennis forehand stroke under different spatial and temporal constraints. Two main results emerged from the study, which are the focus of this discussion. First, although medication significantly reduced the gaze frequency of the ADHD-On group, this did not lead to an increase in their pursuit tracking duration on the ball. This suggests the ADHD groups were unable to process the long-duration information posed by the pre-cue and the moving ball. Second, the arm movements of the ADHD individuals were normal in the short-duration early-cue condition, but impaired in the long-duration pre-cue condition. These findings suggest that individuals with ADHD are unable to process long-duration visual information critical to normal motor performance, but can process short-duration information without experiencing the same extent of adverse effects.

The normal adolescents exhibited gaze and arm control characteristics that were very similar to adults in tasks of a similar nature (Bootsma, 1988; Ripoll and Fleurance, 1988; Rodrigues et al., this issue). They initiated tracking immediately after the ball was served and maintained quiet eye tracking over approximately 50% of early ball flight, or about 400–420 ms. Their movement time onset, movement time duration and arm velocity at contact were similar to those of adults, as was their accuracy (46.4%). High skilled adults in the same task had an accuracy of 49.5% (Rodrigues et al., this issue). Normal perception-action coupling was evident, as supported by significant correlations in all gaze and motor comparisons, in line with the results of Bootsma (1988) and Bootsma and van Wieringen (1990) for adults.
The accuracy of the control group differed significantly from that of the ADHD-On and ADHD-Off groups, who had very low accuracy (25.5% and 29.5% respectively). Such low accuracy is similar to that found by Rodrigues et al. (this issue) for high and low skilled adults in a late-cue condition, where the target was cued with only 300 ms left to respond. Accuracy in this condition was greatly reduced (30.3%) irrespective of skill, indicating a threshold had been reached that precluded normal motor performance.

The ADHD-Off group averaged 3.83 gazes per trial versus 2.34 for the controls. The use of medication significantly reduced the gaze frequency of the ADHD-On group to a value more similar to the controls, indicating medication in the form of Ritalin or Dexedrine had a quieting effect on their gaze. Surprisingly, this did not lead to an increase in tracking duration, which averaged 38.9% of ball flight when on medication and 36.4% when off it, a difference of about 20 ms. The ADHD groups’ accuracy was higher when their gaze frequencies were higher, unlike the controls, who achieved better accuracy when they had a low gaze frequency. Only by repeatedly trying to see the moving ball were the ADHD individuals able to deduce its flight and achieve even low accuracy.

The inability to sustain tracking on a moving object and the higher frequency of gaze are in line with the results of Jacobsen et al. (1996) and Ross et al. (1994). However, in a recent study with adults, Ross et al. (2000) found no differences between ADHD individuals and controls in pursuit tracking. A possible reason for the discrepancy may lie in the nature of the continuous duration task used, where the object moved in a predictable manner, in contrast to the variable flight path of the ball in the current study. It may be that, in continuous tasks, the cognitive processes of individuals with ADHD are sufficient to sustain tracking for an extended period; however, in table tennis, the flight path of the ball was never the same from trial to trial, nor was the location of the target, thereby requiring the constant updating of critical movement information. Deficits in gaze pursuit among individuals with ADHD may, therefore, be specific to visual stimuli that are constantly changing, rather than continuous.

*Visuo-motor control of ADHD individuals and controls*

A central characteristic of motor coordination is the ability to control both the speed and direction of the limbs in pursuit of goal-directed behaviours. In a skill such as table tennis, movement time onset must be timed with the approaching ball exhibiting anticipation timing that is dependent on the adequate processing of ball direction and speed. Movement time onset of the ADHD groups was significantly later in the long-duration pre-cue condition, indicating an inability to effectively use the information acquired early in the task to anticipate the arrival of the ball. Velocity control of the limbs is also important and is ‘the rate of change of position with respect to time. In other words, how rapidly did the change in position occur and in what direction’? (Enoka, 1994, p. 3). A table tennis surface is constructed so that too much arm velocity, or an ill-timed movement time onset, will carry the ball beyond the table, while too little will send it into the net, or short of the target. End-point velocity control, or velocity at contact, is critical in motor performance, as it offers the choice of maximum output or more tempered control given the nature of momentary task constraints. In the short-duration early-cue condition, the ADHD participants’ movement time onset, movement time duration and arm velocity at contact were similar to those of the controls irrespective of medication. However, in the long-duration pre-cue condition, the ADHD groups differed from the controls in movement time onset and/or arm velocity at contact.

With a movement time duration of 200–238 ms for all groups, it is likely that the action of the arm was pre-programmed and run off in open-loop fashion (Schmidt and Lee, 1999). When the ADHD individuals had very little time to see the cue, it appeared that, unlike the controls, organizing the motor program was unaffected; however, in the pre-cue condition, where it was necessary to fixate the target cue, then the server and then track the approaching ball, they were unable to construct a motor program that contained the appropriate movement time onset and velocity control parameters. These results suggest that, in the pre-cue condition, information was not being processed adequately between the short- and long-duration visuo-motor systems, but instead appeared to be ‘contaminated’ as processing time increased (Rossetti, 1998), resulting in an inadequate programming of the arm action. Recall that the gaze behaviours of both the ADHD-On and ADHD-Off groups were irregular in both the pre-cue and early-cue conditions; therefore, the more likely source of contamination was the pre-cue, which was illuminated 2 s before the serve, followed by a ball flight that accounted for approximately 850 ms. The pre-cue, once fixated, had to be stored in memory as the gaze was directed to the server and then to the approaching ball. Storing this critical spatial information within the motor program and updating its relevance in terms of the approaching ball and control of the arm appeared to present a problem for the ADHD participants.

The results show that ADHD adolescents differed significantly in gaze frequency and quiet eye duration – gaze control variables that indicate they were unable to
control their gaze on the ball for a long time. A limit appeared to be reached at 300–330 ms, where tracking was interrupted by saccades followed by an attempt to resume tracking later in flight. The ADHD participants’ shorter tracking attempts indicated that they received a brief glimpse of the ball than controls and, to deduce its pathway, they had to try repetitively to see the ball over its flight, resulting in a significantly higher gaze frequency. This explains in part why the ADHD groups performed with less skill than the controls; either they did not receive enough ball flight information to perform at high skill or the visual information they did receive was too contaminated or fragmented to be of normal use.

Response inhibition or a deficit in processing long-duration visual information?

In the final part of the Discussion, we consider whether the irregular gaze and arm control of the ADHD groups was due to a deficit in response inhibition (Ross et al., 1993, 2000; Douglas, 1999; Schachar et al., 2000) or, alternatively, to a deficit in processing long-duration visual information critical to effective motor performance (Rossetti, 1998; Tannock, in Paule et al., 2000). Tannock has suggested that ADHD may be associated with impairments in the precise representation of temporal information integral to motor performance. Neither perspective can be supported conclusively by the results of this study; however, four lines of evidence suggest that a core deficit of ADHD may be an inability to process long-duration visual information critical to motor task performance.

First, medication had a calming effect on the gaze frequency of the ADHD-On group, leading to a significant reduction in the number of gazes per trial when on medication. However, this did not lead to an increase in quiet eye tracking duration. Instead, a barrier appeared to be reached at 300–330 ms where ball tracking ceased, suggesting ball flight information was not being processed to a deeper level. Because of this, the saccadic system may have been triggered to access new ball flight information resulting in the higher gaze frequency. This may also account for the premature use of saccades found in other studies (e.g. Ross et al., 1994).

Second, greater accuracy was recorded for the ADHD groups when their gaze frequency was higher; in contrast, the controls were more accurate when their gaze frequency was lower. The high gaze frequencies of the ADHD groups suggested that they were unable to process the continually changing ball flight information and had to repeatedly try to see the ball to deduce its flight path. In light of the results of Ross et al. (2000), this deficit may be specific to rapidly changing information that must be accessed for a long duration, stored in memory and updated for an effective motor behaviour to be performed.

Third, the movement time onset and arm velocity at contact of the ADHD groups were normal in the short-duration early-cue condition, but abnormal in the long-duration pre-cue condition, suggesting a contamination of the movement arising from the pre-cue and/or the longer flight duration of the ball, which was unimpeded by the imposition of a cue or other distracter. When long-duration information had to be held in memory and processed, it appeared to ‘contaminate’ (Rossetti, 1998) the motor behaviour of the ADHD participants, resulting in irregular movement time onset and velocity control of the arm. In the early-cue condition, the presence of the later cue appeared to override this contamination and allowed the short-duration system to function in an adequate, but at a still lower level than the controls when both systems worked together. When there was not enough time for task information to be passed from the short- to the long-duration system, this appeared to lead to more normal movement time onset and arm velocity at contact.

Although speculative, the inability of the ADHD groups to control their movement time onset and arm velocity in the long-duration pre-cue condition, but exhibit normal motor control in the short-duration early-cue condition, may explain why hyperactivity is a characteristic of so many individuals diagnosed with ADHD. It is only when the pace of events is speeded up that they experience normal control over the speed and direction of their limbs.

Fourth, the complete absence of perception-action coupling between the gaze and arm control variables of the ADHD groups provided additional support for a deficiency in information processing. Unlike the high and low skilled individuals in the study of Bootsm (1988) and the controls in the current study, the ADHD participants exhibited no correlation between the timing of their gaze and performance of the arm action.

Potential implications

Children and adolescents with attention deficit hyperactivity disorder are drawn to fast-paced tasks, while eschewing those that require concentration and focus over extended periods of time (Douglas, 1972, 1999; Barkley, 1998; Paule et al., 2000). If the core deficit of ADHD is a deficit in processing long-duration information, then parents, doctors, educators and clinicians may be well advised to create opportunities for ADHD children and adolescents to be involved in long-duration tasks that require concentration and focus over time. Precedents for this recommendation exist in the literature. Barkley (1998) reports that, in the past, teachers were advised to create learning environments that were
quiet and had few distractions, so children with attention and hyperactivity problems could develop concentration and problem-solving skills. Pope and Bogart (1996) have designed a flight simulator that rewards sustained attention and vigilance, rather than quick ballistic eye and hand movements so common in many video and electronic games. Finally, with the advent of television and computers, there are many opportunities for youngsters to strengthen the short-duration visuo-motor system, while possibly impairing the long-duration system, making inattention, inhibition and hyperactivity more likely. Long-duration visuo-motor activities that promote the development of more extensive neural networks may facilitate the development of the short- and long-lived visuo-motor systems. This may be especially important when children are young, as neural development occurs very rapidly at this time. However, in concluding, we note that the current findings need to be considered with caution given the small sample size and the failure to assess participants over a wider age range. Future studies should consider a variety of time delays and diagnostic group memberships.

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References


