Head–torso–hand coordination in children with and without developmental coordination disorder

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AIM This study investigated the nature of coordination and control problems in children with developmental coordination disorder (DCD).

METHOD Seven adults (two males, five females, age range 20–28y; mean 23y, SD 2y 8mo) and eight children with DCD (six males, two females, age range 7–9y; mean 8y, SD 8mo), and 10 without DCD (seven males, three females, age range 7–9y; mean 8y, SD 7mo) sat in a swivel chair and looked at or pointed to targets. Optoelectronic apparatus recorded head, torso, and hand movements, and the spatial and temporal characteristics of the movements were computed.

RESULTS Head movement times were longer (p<0.05) in children with DCD than in the comparison group, even in the looking task, suggesting that these children experience problems at the lowest level of coordination (the coupling of synergistic muscle groups within a single degree of freedom). Increasing the task demands with the pointing condition affected the performance of children with DCD to a much greater extent than the other groups, most noticeably in key forward kinematic landmarks. Temporal coordination data indicated that all three groups attempted to produce similar movement patterns to each other, but that the children with DCD were much less successful than age-matched children in the comparison group.

INTERPRETATION Children with DCD have difficulty coordinating and controlling single degree-of-freedom movements; this problem makes more complex tasks disproportionately difficult for them. Quantitative analysis of kinematics provides key insights into the nature of the problems faced by children with DCD.

Children with developmental coordination disorder (DCD) show profound difficulties in a range of motor tasks, despite normal IQ and no evidence of neurological, biological, or physical impairment.¹ The consequences of DCD are severe, and studies have linked poor movement skills in early childhood with poor educational outcome² and social and emotional difficulties.³ Unfortunately, the factors that contribute to their poor execution of actions are not well documented and there is a pressing need for such data.

The name of the disorder suggests that the problem is one of coordination. However, there are at least three broad levels at which a coordination difficulty might arise in DCD. First, even a single behavioural degree of freedom (e.g. turning the head) requires the coordination of numerous elements. Second, deficits might not arise until two or more degrees of freedom or effectors need to be coordinated (e.g. turning the head and torso). Third, both of these may be intact, but deficits might still arise when coordinating with external factors or objects.

This study investigated the type of coordination difficulties experienced by a population of children with DCD. Two everyday tasks that have received remarkably little attention – moving the head to look at a target and moving the hand to point at a target⁴– were used because they allowed us to vary the task complexity across the noted levels. In the looking task, participants simply looked at targets on either side of a central target; the targets were located in positions that elicit gaze shifts through head rather than eye movements.⁴ This task could be accomplished through a single degree-of-freedom rotation of the head relative to the shoulders. We reasoned that deficits here would indicate coordination problems at the first suggested level. The pointing task was more complex as it required movement of the arm and head. Moreover, targets on the contralateral side (opposite the pointing hand) required rotation of the torso (through chair movement). Thus, the pointing task required coordination of multiple body segments. Group differences in this task, in the absence of group differences in the looking condition, would indicate
deficiencies in the second suggested level. A lack of group differences in either looking or pointing tasks would prompt us to investigate other factors to understand coordination problems in DCD.

Coordination is not the only potential problem. Therefore, we also examined kinematic data to assess the integrity of the control processes in DCD. One suggestion is that children with DCD may have a problem with preprogramming movement times and ‘time to peak speeds’ (TPS) compared with typically developing children.6,7 The time from movement onset until TPS is generally accepted to index the part of a movement under preprogrammed, feedforward control. The time from TPS until movement offset (deceleration time) is when the movement comes under feedback control (generally visual).8,9 Deficits in feedforward control are reflected in differences in the magnitude of peak speed and/or the TPS, and deficits in feedback control are reflected by group differences in deceleration time.

In summary, we investigated looking and pointing behaviour in children with DCD and in a comparison group of age-matched children and adults. The paradigm allowed us to separate out various levels of coordination, as well as to study feedforward and feedback processes.

**METHOD**

**Participants**

There were three groups: (1) seven adults (five females, two males) age range 20 to 28 years (mean age 23y, SD 2y 8mo) were recruited from the University of Aberdeen. All of the adults had normal or corrected-to-normal vision and none reported any movement abnormalities or disabilities. (2) Eight children (two females, six males) age range 7 to 9 years (mean 8y, SD 8mo) with DCD were recruited through the Occupational Therapy Department at the Royal Aberdeen Children’s Hospital. These children all scored below the 5th centile on the Movement Assessment Battery for Children.10 All participants were right-handed. Parental permission was provided for each child to participate, and parents were invited to observe during data collection. Complete sets of data that could be included in the analyses were obtained from only six of the eight children. The two females produced results that were qualitatively different from the males and their behaviour will be discussed separately. (3) Parent/guardian letters of invitation to participate were distributed to an Aberdeen primary school in order to recruit age-matched comparison children. From those who agreed to participate, the reply slips were shuffled and the 10 children (three females, seven males; age range 7–9 years, mean 8y, SD 7mo) were selected to participate in this study. None reported any movement abnormality.

The study received ethical approval from Aberdeen University and the NHS Grampian Ethics Committee.

**Apparatus and procedure**

Participants sat in a standard office swivel chair with a fixed base placed in the centre of a room, 226cm from the walls. The height of the chair was adjusted for each person so that the participants’ feet were flat on the floor, with the hips and knees at approximately 90° relative to each other. The participants were asked to either look or point with a hand-held laser (with arm extended) at targets mounted at 30° intervals on the wall around them. The targets measured 5cm × 27cm, were numbered 1–6, and were placed at eye level for all participants. An unnumbered target was the ‘home’ position (see Fig. 1). In total, each participant received three practice trials followed by 48 test trials of looking and 48 of pointing (eight to each of six targets in a randomized order, blocked by task).

The positions of the head, chair, and hand were monitored using Optotrak (NDI Europe GmbH, Radolfzell, Germany), factory precalibrated to a static positional resolution of better than 0.2mm at 250Hz. Data were collected for 4 seconds at 100Hz. Two infrared-emitting diodes were placed on rigid frames mounted on the head, chair, and wrist. The frames increased the spatial separation of the markers so that small angular rotations of the effectors produced large movements of the infrared-emitting diodes, increasing our ability to detect the movements. In the pointing condition, participants held the laser pointer so that their index finger was aligned along the length of the laser. Participants started each pointing trial with their arm pointing downwards by the side of their body. On the ‘go’ signal, participants were instructed to first point at the ‘home’ target with their arm outstretched and then to move to the target location whilst keeping their arm straight.

The stored data files were analysed using Labview 8 (National Instruments Corp., Austin, TX, USA). The data were filtered using a dual-pass Butterworth second-order filter with a cut-off frequency of 16Hz (equivalent to a fourth-order zero-phase lag filter of 10Hz). The tangential velocity of the markers was computed, and these signals were combined to generate a resultant speed profile of the movement. The speed profiles were used to determine the onset and offset of the movement using a standard algorithm (threshold for movement onset and offset was 7°/s). Movement time was the difference between onset and offset of movement. Peak speed, TPS and deceleration time were also computed, as were the signed and unsigned (i.e. the absolute values) differences in movement onset and offset. The unsigned data index the

**Figure 1:** Schematic of experimental set-up. Targets were located at eye level at a fixed distance to the right and left at 90°, 60°, and 30° from the participant in the chair. The starting ‘home’ target was along the midline.
magnitude of temporal asynchrony, whereas the signed data index temporal ordering between segments.

For each participant and each condition, the median value of the eight measurements of the variables of interest was analysed (the median is robust to outliers). For all analyses, the α-level was set at 0.05.

RESULTS

Qualitative observations

The children with DCD found it difficult to sit upright in the chair, had problems holding their arm up during the pointing task, and struggled to maintain balance on trials in which the chair moved. The children sometimes bent their arm to point at peripheral targets rather than keeping their arm extended. This strategy aided them but meant that they failed to obey task instructions. These trials were replaced at the end of the session. The two females with DCD both produced data that were qualitatively different from the other participants, as they used a strategy of shuffling their feet along the ground until they reached the target location, thereby locking out the degrees of freedom normally associated with coordinating movements between body segments. These two children were excluded from the group kinematic analysis.

Kinematic data (Head)

All kinematic analyses across task were performed on head movements, the common feature of the looking and pointing tasks. All analyses of variance (ANOVAs) were mixed design, with task (two levels: looking, pointing) and target location (six levels: 0°, 30°, 60°, 120°, 150°, 180°) as within-participant factors, and group (three levels: DCD, comparison children, comparison adults) as a between-participant factor. Differences due to target location were expected (kinematics vary with target distance, etc.) and so will not be analysed in detail – the key results are between task and group. We also collapsed target location over contralateral versus ipsilateral movements as there was no statistically reliable difference between these movements.

Head movement time (Fig. 2a)

Movement time is a useful measure of task difficulty; in general, movement time increases when a task is more difficult. There was a main effect of task ($F_{(1,20)=14.55; p<0.01}$). Movement time was significantly longer in the pointing condition than in the looking condition. There was also a main effect of group ($F_{(2,20)=11.96; p<0.01}$). Planned pairwise comparisons showed that this effect was caused by the movement times of the children with DCD being longer than those of both adults and children in the comparison group, which were not significantly different from each other. No other effect was significant.

Head peak speed, time to peak speed, and deceleration time

The primary component of the movement pattern for all groups was a bell-shaped speed profile. This profile was seen in the head, chair and finger movements. The prevailing consensus is that peak speed and TPS reflect stages under feedforward control, whilst deceleration time reflects stages under feedback control. We therefore analysed these variables across the groups.

(1) Peak speed. There was a main effect of task ($F_{(1,20)=77.2; p<0.01}$) and target ($F_{(5,100)=90.9; p<0.01}$), but these were modified by a significant task × target interaction ($F_{(5,100)=4.2; p<0.01}$). There was also a target × group interaction ($F_{(10,100)=3.30; p<0.01}$). The children with DCD reached a lower peak speed to the further targets but a higher peak speed to the intermediate targets than children in the comparison group.

Figure 2: Head kinematics as a function of group (children with developmental coordination disorder [DCD] comparison children, and adults) and task in (a) movement time, (b) time to peak speed, which typically reflects feedforward control time, and (c) deceleration time, which typically reflects feedback control time. The results suggest that the large increase in movement time in the children with DCD is primarily caused by changes in the feedforward part of the action.
(2) Time to peak speed (Fig. 2b). There was a main effect of task \((F_{(1,20)}=87.1, p<0.01)\), target \((F_{(5,100)}=3.7, p<0.01)\), and group \((F_{(2,20)}=55.4, p<0.01)\), but these were modified by two interactions. There was a significant task \(\times\) target interaction \((F_{(5,100)}=8.1, p<0.01)\) and a significant task \(\times\) group interaction \((F_{(2,20)}=35.4, p<0.01)\). The latter revealed that the children with DCD showed a larger increase in TPS from the looking to the pointing task than the comparison children or adults. The significant results in TPS might be driven by the observed changes in overall movement time. To investigate this, we repeated the ANOVA on TPS expressed as a proportion of movement time (Fig. 3a). There was a main effect of task \((F_{(2,20)}=9.9, p<0.01)\) but, most importantly, both interactions remained significant (task \(\times\) group: \(F_{(2,20)}=9.2, p<0.01\); task \(\times\) target: \(F_{(5,100)}=2.8, p<0.05\)). This result suggests that the changes in movement time were not the cause of the changes in TPS, rather the reverse. Most of the difficulty experienced by the DCD population was in the feedforward component of the movements, before peak speed.

(3) Deceleration time (Fig. 2c). There was no significant main effect or interaction in deceleration time. We repeated the ANOVA with deceleration time expressed as a proportion of movement time (Fig. 3b). There was a main effect of task \((F_{(1,20)}=6.5, p<0.01)\) and group \((F_{(2,20)}=3.6, p<0.05)\), but these were both modified by a task \(\times\) group interaction \((F_{(2,20)}=4.5, p<0.05)\). Children with DCD spent relatively less time decelerating in the pointing condition than both adults and children in the comparison group, reflecting the fact that they spent so much more of their total movement time in the early phase of the movement.

Coordination data

Coordination data are all from the pointing task; the inclusion of the adult group allowed us to interpret the results in the context of the most skilled strategy. We computed both signed and unsigned onset and offset asynchronies for head–chair, head–finger, and chair–finger. Signed asynchronies provide a measure of the temporal ordering of the movements, while unsigned asynchronies provide a measure of the magnitude of differences. All ANOVAs were mixed design, with coordination (three levels: head–chair, head–finger, chair–finger) and target location (six levels: \(0^\circ, 30^\circ, 60^\circ, 120^\circ, 150^\circ, 180^\circ\)) as within-participant factors, and group (three levels: children with DCD, comparison children and adults) as a between-participant factor (Fig. S1, supporting information published online).

Signed and unsigned onset asynchronies

In the signed onset data, there was only a main effect of coordination \((F_{(2,40)}=21.9, p<0.01)\). There was no effect involving group; children with DCD and comparison children and adults started the movement of the head, chair, and arm at about the same time, on average. The unsigned onset data did show a main effect of group \((F_{(2,20)}=5.4, p<0.05)\), in which the DCD population showed a greater overall onset asynchrony than the adults (i.e. more variable coupling of the components). Overall, all groups began the three movements at roughly the same time, but the children with DCD were less skilled.

Signed and unsigned offset asynchronies

In the signed offset data, there was a significant main effect of coordination \((F_{(4,40)}=36.5, p<0.01)\), and significant coordination \(\times\) group \((F_{(4,40)}=2.6, p<0.05)\) and coordination \(\times\) target \((F_{(10,200)}=5.6, p<0.01)\) interactions. In all groups, the chair stopped moving before either the finger or the head, which stopped at approximately the same time as each other; the coordination \(\times\) group effect showed that the adults were more tightly coupled than the children.

In the unsigned data, there were significant main effects of group \((F_{(2,20)}=4.8, p<0.05)\) and target \((F_{(5,100)}=3.1, p<0.05)\), and significant coordination \(\times\) group \((F_{(4,40)}=5.6, p<0.01)\) and coordination \(\times\) target \(\times\) group \((F_{(20,200)}=2.1, p<0.01)\) interactions. The coordination \(\times\) group interaction showed that the DCD population showed much less coordination between the finger and the head or chair. This reflects their difficulty in controlling the hand as they swung it around to point at a target. The head and chair were more tightly coordinated in the children with DCD than in the other two groups, suggest-
ing that these children were relying on the chair to help control their head movements.

Overall, the chair stopped first, followed by the head and finger. The children with DCD also attempted to do this, but had much less success than either the comparison children or adults. In general, the children performed a version of the skilled adult strategy, rather than adopting a different solution that reflected their maturational state.

DISCUSSION
The present study used a relatively small number of participants. This was a necessity because of the technical difficulties in running experiments of this complexity with children, with or without DCD. Nonetheless, the quantitative differences found between groups were profound — the children with DCD found both looking and pointing tasks difficult in comparison with their peers. Most notably, the children with DCD had difficulties in the looking task (i.e. longer movement time), in which success required only a single rotation of the head relative to the torso. This suggests that the coordination difficulties experienced by the children with DCD were at a single degree-of-freedom level. This interpretation is supported by the pointing results, which showed that children with DCD were disproportionately affected by the increase in task complexity relative to the other groups. It is true that simply moving the head relative to the torso is not a trivial control problem. Nonetheless, we suggest that difficulties with this fairly common and typical one degree-of-freedom action suggest quite fundamental control problems. It is, therefore, unsurprising that the children perform so poorly on the complex tasks contained in standardized movement assessment batteries (e.g. the Movement Assessment Battery for Children).

The results also suggest that not all control processes are equally affected in DCD. The kinematic analyses suggest that much of the difficulty is in the feedforward part of the movement. This was indexed by the increase in TPS in DCD compared with the comparison groups even when the overall increase in movement time is controlled for. These data are consistent with other studies that have found similar problems in the child being able to stay on task and complete his or her work in good time. These difficulties might account for the fact that children with DCD often meet the diagnostic criteria for ADHD. Our results suggest that improving the stability of the postural platform with special seating might simplify the task faced by these children and allow them to focus on taught material.

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SUPPORTING INFORMATION
Additional supporting information may be found in the online version of this article:

Figure SI: Temporal coordination data from the pointing task, as a function of group (children with developmental coordination disorder [DCD], comparison children and adults) and coordination type. The top row shows onset asynchronies; the bottom row shows offset asynchronies. The left column shows signed asynchronies and the band d shows unsigned asynchronies. The results suggest that the groups all attempted to produce essentially the same coordination pattern (three distinct movements starting at the same time, with the chair finishing before the head or finger), although the children with DCD were much less skilled (greater unsigned asynchronies) than the comparison adults or children.

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