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The use of predictive information is impaired in the actions of children and young adults with Developmental Coordination Disorder

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Abstract

The need for a movement response may often be preceded by some advance information regarding direction or extent. We examined the ability of individuals with Developmental Coordination Disorder (DCD) to organise a movement in response to advance information. Pre-cues were presented and varied in the extent to which they indicated the response target. Both eye movement latencies and hand movements were measured. In the absence of pre-cues, individuals with DCD were as fast in initial hand movements as the typically developing (TD) participants, but were less efficient at correcting initial directional errors. A major difference was seen in the degree to which each group could use advance pre-cue information. TD participants were able to use pre-cue information to refine their actions. For the individuals with DCD this was only effective if there was no ambiguity in the advance cue and they had particular difficulty in using predictive motion cues. There were no differences in the speed of gaze responses which excluded an explanation relating to the dynamic allocation of attention. Individuals with DCD continued to rely on the slower strategy of fixating the target prior to initiating a hand movement, rather than using advance information to set initial movement parameters.

Introduction

An intended movement must be parameterized for direction and extent before a response can be executed. In everyday settings movements are often made in response to an external cue. For example computer operating systems routinely display pop-up dialogue boxes, in random areas of the screen, which require a response. In human interaction a teacher may point to an object, and say “use this” or “use that”. Pre-specifying direction or providing advance information regarding the location of a target enables the programming of a movement before a response is required (Rosenbaum, 1980). Pre-programming movements is thought to increase the efficacy of the initial distance covered during the ballistic part of a movement (Schellekens, Kalverboer, & Scholten, 1984). This is thought to reduce the demand for online corrections, thus speeding up the movement and freeing processing capacity (Van Dellen & Geuze, 1990).

The pre-programming of responses in children and adults (aged 6yrs, 8 yrs, 10yrs and 22yrs) has been investigated using valid pre-cues, invalid pre-cues and neutral pre-cues (Olivier, Audiffren, & Ripoll, 1998). Olivier et al. (1998) suggest that from 6 years of age children use pre-cue information to prepare movements in advance and the costs and benefits of pre-planning a motor response does not differ with age. Olivier & Bard (2000) looked at 7, 9 and 11 year-olds and examined control when there were no cues; a directional pre-cue; an amplitude pre-cue; and a pre-cue that included both direction and amplitude. Pre-cueing spatial dimensions of a movement shortened the reaction time of the hand and this was a function of the number of dimensions cued. Again, Olivier & Bard (2000) found no age related differences in the pre-programming of responses. Van Dellen & Geuze (1990) also demonstrated that children as young as 6 years can use auditory pre-cues in the pre-programming of a movement response. This study also demonstrated an age related improvement in the response to advance information from 7 years to 12 years of age (Van Dellen & Geuze, 1990). Both duration and accuracy of the initial ballistic phase of the movement increased with age as did the relative measure of the advantage gained with precuing. These findings suggest that older children anticipated movement better than younger children. The contrast in the findings of Olivier & Bard and Van Dellen & Geuze suggests that the degree of advantage seen in pre-cueing paradigms may be task dependant.

Within the normal population a small proportion of children (~5%) present with difficulties in the coordination of eye and body movements. These deficits cannot be accounted for in terms of an intellectual impairment or identifiable physical disorder (American Psychiatric Association, 1994). This condition has been termed Developmental Coordination Disorder (DCD). DCD is often found to occur in a greater number of males than females (Gordon & McKinlay, 1980). Children with DCD have problems which manifest in difficulties with fine motor tasks such as tracing, writing and fastening buttons, and/or in gross motor tasks such as jumping, hopping and catching a ball (Sugden & Wright, 1998). Children with DCD continue to exhibit problems throughout adolescence and do not simply grow out of their coordination problems (Losse et al., 1991). Despite an increasing number of studies focusing on DCD very little is known about the underlying cause of the movement problems exhibited in DCD (see Visser, 2003 for a review).

Wilson, Maruff, & McKenzie (1997) suggested that children with DCD have a cognitive deficit which impairs their ability to use advance information. This conclusion was based on the finding that children with DCD display a difficulty in using the alerting properties of peripheral spatial cues to prepare motor responses: children with DCD did not show facilitation to a prolonged temporal gap between cue onset and presentation of a target; and children with DCD showed a disproportionate increase in manual reaction time on invalid cue trials. Supporting the theory that children with DCD have an impaired ability to use advance information, Van Dellen & Geuze (1988) have shown clumsy children are unable to pre-plan movements based on auditory cues.

More recently, Mon-Williams et al. (2005) investigated three different cue types using four target locations: *full cues*, where target information was unambiguous and only one target was cued; *partial cues*, where left or right areas were cued, highlighting two possible targets and; *null cues*, where cue information was ambiguous and all targets were cued. Adults, typically developing (TD) children and children with DCD completed a series of reach-to-grasp tasks under these cue conditions. Mon-Williams et al. (2005) found that adults and TD children showed a decrease in the reaction time of the hand for both the full cue and the partial cue; this decrease was more pronounced for the full cue. Although the children with DCD showed a clear advantage when presented with a full cue, the movement times in partial cue conditions were similar to those in no cue conditions. Consequently, it seems that the children with DCD are not using partial or incomplete advance information to plan a response. A partial cue allows the preparation of a movement to a generalised location, which is then updated once the exact target location is known. Mon-Williams et al. (2005) proposed that "……*it is only worth employing this strategy if you can make the required corrections online and maybe the 'costs' of implementing this strategy is too high for children with DCD*". This theory, that the 'costs' are too high for children with DCD, is supported by a previous finding by Mandich, Buckolz, & Polatajko (2003) who showed that children with DCD find it harder to modify planned movements or to stop the execution of a primed movement.

Although pre-programming a response can be achieved using a static cue it can also be achieved using a moving or dynamic cue. A pencil rolling towards the edge of a desk prompts the preparation of a motor response to catch the moving object before it drops to the floor. In this case end target location is not pre-specified and so has to be extrapolated in real-time from the motion of the cueing object. Previous research has suggested that anticipating and intercepting location may be a problem in three to five year-old children (Bairstow, 1987, 1989) and in children with motor coordination problems (Bairstow & Laszlo, 1989). Sugden & Sugden (1992) also suggest that children with DCD can show a specific deficit in the interception of moving targets and that this distinct from other movement control problems. Research by Estil, Ingvaldsen, & Whiting (2002) has also shown that children with movement coordination problems show larger temporal and spatial errors when predicting the final location of a moving ball, they concluded that this was due to a visuo-spatial anticipation problem whereby more time was needed to appreciate the direction of the ball. We are unaware of any research that has looked at the utilisation of dynamic cues in children with DCD; however, we would predict that these would pose a particular problem for individuals with DCD.

The current experiment aimed to extend the research on static cues to include directional motion cues. This study used a wider age range than previous studies with participants ranging from 6 to 23 years. We utilized four different cueing conditions: static cues presented peripherally around the targets (as used by Mon-Williams et al., 2005; Wilson et al., 1997); static cues presented centrally indicating peripheral targets (as used by Wilson et al., 1997); predictive motion cues with 4 possible target locations; and predictive motion cues with 12 possible target locations.

The static peripheral cues were used to validate our methodology, replicating the Mon-Williams et al. (2005) study. Centrally displayed cues were used to bridge the gap between peripheral static cues and central predictive motion cues (dynamic cues radiated out from a central position towards the periphery). By increasing the number of target locations in the predictive motion cueing condition we forced a higher level of spatial prediction and real-time extrapolation to determine direction of motion. Within all cueing conditions we also varied the specificity of the advance information provided. For static cueing either full cue information (target indicated) or partial cue information (left vs. right side) was provided. Again this aimed to replicate and extend the Mon-Williams et al. (2005) study by considering levels of ambiguity in cue information. For the predictive motion conditions all targets were unambiguous, i.e. the predictive motion always moved towards a single target. In order to mimic the cue type (i.e. full vs. partial) of the static cueing condition we manipulated the temporal and spatial aspect of the motion cues. This was done by presenting a sequence of dots radiating outwards towards a target, each dot appeared for 100ms and then disappeared. The sequence of dots was either made up of 6 dots (600ms, spatially closest to the target), 4 dots (400ms) or 2 dots (200ms, spatially furthest from the target). In this way the three cue types provided a different degree of likelihood for target specification. The cued conditions were compared to trials in which no cue was provided as a baseline performance measure.

The previous contrasting findings regarding the use of pre-cues in children may be attributed to the differences across tasks. Pre-cueing information presented centrally, that provides direction information is not directly comparable to cueing in the periphery, which provides location (direction and extent) information. For this reason we do not explicitly compare the advantage gleaned from central, peripheral and motion cueing, but concentrate on the between group effects and the level of specificity within each condition.

Another factor where one might surmise that there could be a difference between TD children and children with DCD is the allocation of attention. A standard precuing paradigm affords the covert allocation of attention prior to movement initiation. Rizzolatti and colleagues have presented strong behavioural and neural evidence for their pre-motor theory of covert attention (Rizzolatti, Riggo, Dascola, & Umilta, 1987), therefore you might expect a participant who had difficulty in preparing movements to have difficulty in dynamically allocating spatial attention. Can the effects of oriented attention and movement preparation be separated? We would argue that they can: firstly a general deficit in the allocation of spatial attention is not consistent with the differential effects observed by Mon-Williams et al (2005) where the children with DCD were efficient in some cueing conditions but not others; secondly, the pre-motor argument is largely built upon eye-movements response times. Therefore, attentional effects should be reflected in both eye and hand movements (Sheliga, Craighero, Riggio, & Rizzolatti, 1997), whereas effects observed in hand movements but not gaze shifts would be attributed to the preparation of the manual response. In this respect differences in eye and hand onset latencies (eye-hand lead) across tasks and groups may be an informative variable.

Improvement in response time is deemed to be due to the more efficient/early coding of direction and/or amplitude. For this reason a number of previous studies examining pre-cue effects have used response (reaction) time as the primary means of assessment. We measured both eye and hand movements to determine whether an advantage is seen in either system. We also included more direct measures of the accuracy of the initial hand movement direction and any subsequent adjustments each participant needed to make to their hand trajectories. Our hypothesis was that, similar static cueing effects will be observed as found in Mon-Williams et al. (2005), but that predictive motion cues would provide a particular difficulty for individuals with DCD. We had no prior hypotheses as to whether the effects will be reflected purely within the manual responses or in also in the gaze responses, the latter being consistent with more general argument related to spatial attention.

As a final factor to consider it has been suggested that children with DCD may show specific problems with different classes of visual processing. Tests of form coherence have been shown to test ventral stream function (Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000) while tests of motion coherence have been shown to test dorsal stream function (Scase, Braddick, & Raymond, 1996). Studies that have used form and motion coherence tests to look for a selective impairment in children with coordination problems have yielded contrasting results. Stein & Walsh (1997) found a deficit in dorsal stream function in a group of children with developmental Dyspraxia. O'Brien, Spencer, Atkinson, Braddick, & Wattam-Bell (2002) found a specific deficit in ventral stream function in a group of Dyspraxic children and Sigmundsson, Hansenc, & Talcott (2003) found a deficit in both dorsal and ventral stream function in a similar group of children. In these studies children were allocated to groups based on very different assessment methods and were classified very differently (Developmental Dyspraxia, Dyspraxia, clumsy), such large differences in the identification of children could explain the disparity in these findings. In order to consider the possibility of “dorsal stream vulnerability”, which could impact on the utilisation of pre-cues, all participants in our study completed form and motion coherence tasks.

Methods

Participants

This project was approved by a University ethics committee and was performed in accordance with the Declaration of Helsinki. This study included 46 participants, 23 were typically developing (TD) and 23 had Developmental Coordination Disorder. Individuals with DCD were recruited through the Dyspraxia Foundation, UK. The age range of this group was 6 to 23 years. The older participants arose because during this opportunistic sample they contacted us and were keen to participate in the study. We felt we had no valid grounds for rejecting their offer and this provides an interesting comparison of how problems progress after primary school until early adulthood. We therefore split the sample into a young primary school group (6-12 years) and an older secondary school plus group (13-23 years). The latter included six participants between 13 and 16 years and six participants older than 16 years. TD participants were recruited and age matched to within 6 months to each participant with DCD. The TD group was also sub-divided into a primary school and a secondary school plus group. All individuals were assessed using the Movement Assessment Battery for Children (MABC; Henderson & Sugden, 1992). The criterion for clinical diagnosis of DCD is the 5^{th} centile on the full battery, although a number of previous research studies have included children up to the 15^{th} centile in DCD study groups. We feel the 15^{th} centile is too lax, the majority of our DCD participants fell below the 5^{th} centile although we included any participants that fell between the 5^{th} and 10^{th} centiles as borderline/at-risk of DCD, the group means on the MABC were still substantially different (Table 1). All TD participants scored above the 20th centile. Motor competence of participants 13 years of age and above was determined using age band 4 of the MABC. Although this test is not primarily designed to assess motor ability in individuals older than 12 years, only a small gain in motor performance is seen after 10 to 12 years of age for many manual tasks (Annett, 1970; Schulman, Buist, Kaspar, Child, & Fackler, 1969). All older DCD individuals fell below the 10th centile on the MABC and thus were performing badly on a test designed for younger children suggesting a marked motor impairment. All of the 46 selected participants wrote with their right hand, thus all movements were made with the right hand. All participants were also assessed using the WISC-R or the WAIS and all but 11 children fell within 1 standard deviation of the mean (85 to 115). The 11 individuals outside of this range were 6 in the TD group and 5 in the DCD group that scored between 115 and 125. No significant differences, in IQ, were found between the TD and DCD pairings. All participants in the DCD group had received a clinical diagnosis of DCD or Dyspraxia from an occupational therapist or equivalent. During pre-screening we asked parents for details of other medical conditions or developmental disorders, from this it was judged that the DCD participants met criteria A to D of the DSM-IV, but also that their selection was in tune with the 2006 Leeds Consensus Statement (http://www.dcd-uk.org/consensus.html). Although all children in the DCD group had received a clinical diagnosis none of the children had been involved in formal intervention programmes. Therefore, it is likely that these children may have been higher functioning than a group recruited from hospital services.

INSERT TABLE 1 HERE

Apparatus

Participants sat at an 89cm x 61cm table which stood 67cm from the ground. The top of the table was made from 6mm thick Plexiglas® with one satin surface, providing a semi-opaque table top. Underneath the table-top a 6mm thick acrylic mirror lay at a 45^{o} angle and faced away from the participant. A Hitachi CP-X328 projector, positioned 130cm away from the table, projected an image onto the mirror which was then back-projected onto the underside of the table-top and was viewable from above, see Figure 1. The visual display, generated by LabVIEW, consisted of a central red fixation circle surrounded by 4 or 12 targets (see Figure 1 for an illustration of target location). ‘Fluffy bugs’ (~4cm^3) were placed at target locations and remained on the table throughout each trial, these ‘fluffy bugs’ could be illuminated via the back-projected image. The difference in target location across the static and predictive-motion conditions was due to inherent differences in the conditions. In the static condition, targets were divided by midsaggital plane, to allow left/right cueing comparable to previous studies. In the predictive motion condition, targets formed part of an annulus for continuity in the change between 4 and 12 targets while maintaining equivalent movement distance. Starting position of the hand was located on the midline 5cm below the bottom target(s). A Vicon motion capture system (120Hz) was used to track the movement of three reflective markers (6.5mm in diameter) placed on the index finger, knuckle and wrist of the right hand. The motion capture at the beginning of each trial was triggered by a +5v digital signal sent via a National instruments data acquisition card controlled by the LabVIEW programme. Conventional eye-tracking introduces participant constraints that young children have difficulty conforming too, without severely restricting the task. So eye movements were recorded via a Panasonic digital camcorder (60Hz), placed 63cm from the eye, so participants were free to make natural head and hand movements throughout the experiment. The AVI data at 60Hz were integrated, frame-by-frame, within the Vicon digital records (120Hz). This ensured temporal synchronization of the two data sources, but the difference in the sampling rate means that hand events can be resolved to within ~8ms whereas gaze events can only be resolved to within ~17ms and any estimates of eye-hand lead can only be estimated to within the latter limit.

INSERT FIGURE 1 HERE

Procedure

Two static and two predictive motion conditions were measured, each with a differing level of cue information (cue type). In the *static conditions* the cues were presented for 600ms either in the *centre* of the display (an arrow) or they were presented *peripherally* (an area highlighted). Within these cueing conditions two cue types were used: *a full cue*, in which it was unambiguous which target was being indicated or a *partial cue* type (the target bug could be 1 of 2). For the *predictive motion cues* there were either *4 target bugs* or *12 target bugs*, which increased the spatial uncertainty as to which target was being cued. The predictive motion cue was presented as a set of dots radiating outwards towards a target that each appeared for 100ms and then disappeared, in all cases the predictive motion cues were unambiguous and always moved towards one target. We manipulated the temporal aspect of the cue by presenting either *6 dots*, *4 dots* or *2 dots* to provide a total duration for the cue of 600-200ms, respectively. See Figure 1 for an illustration of these conditions. All participants completed all cue conditions and all cue types, they also completed 6 *no cue trials* for each different setup (24 in total). These were run at the beginning of each cueing condition block.

<u>Presentation order</u>

Order of task presentation is a thorny issue for studies with children, particularly those with disorders. The standard paradigm with skilled adult participants is to use a randomised trial order. But one of the commonest findings for research into children with DCD is that they are variable in their performance, both within-subject and within-group. Trial randomisation increases the potential for within-subject variability whereas randomised blocks between participants increases the potential for within-group variability (i.e. some children within a group get an optimal order and some a non-optimal order). The risk when testing children with DCD therefore is that presenting some children with the most difficult task first may inflate movement errors and increase the potential for Type I error, or the variability across the group increases the potential for Type II error. These errors are not managed within a randomized design. In this experiment we opted for a fixed order of presentation going from the simplest and most direct conditions: static peripheral (full cues followed by partial cues; 6 trials each); followed by tasks requiring static cue extrapolation or motion extrapolation: static central (full cues followed by partial cues; 6 trials each); predictive motion 4 target (6 dots, 4 dots, 2 dots; 6 trials each) and; predictive motion 12 target condition (6 dots, 4 dots, 2 dots; 6 trials each). This order allows children to progress from the simplest task to the most difficult task. The consequence of having a fixed order is that the risk of Type I/II error can be assessed. There may be a significant decline in performance across blocks purely due to fatigue/boredom (Type I), but our series of no cue trials at the start of each experimental set-up allowed us to assess this. Alternatively, any between-group differences may be diluted by learning effects across the blocks. Our view of this is that if a difficulty using pre-cues in the DCD group disappears after a short training period then it is not a major developmental problem. This is not a type II error, rather it is the removal of a Type I error through a suitable period of task induction. If, however, a between-group difference occurs because control children adapt better to the increased difficulty, but children with DCD do not, then that is a major issue and does address our central hypothesis. It is worth emphasizing that there is no ideal trial ordering for testing children with movement disorders, but we propose that a fixed order from easy tasks to more difficult tasks optimises the performance of the DCD group and therefore is most appropriate to highlight any persistent difficulties.

Target location was pseudo-randomised for each cueing condition. When there were four target locations, no location was illuminated more than twice. When there were twelve target locations no location was illuminated more than once. All participants used their right, dominant, hand and were instructed to return the hand to the designated starting point after each movement.

Sequence of events

At the start of each block the participants were shown the sequence of events, the nature of the pre-cue that would be presented, i.e. a square in the periphery, an arrow in the centre or dots radiating outwards, and was shown how this would predict the final target location. Participants were then given practice trials (3 per cueing type). The fixation point was illuminated and participants were instructed to fixate this point. Once fixation was achieved, a blue pre-cue appeared which they were told would indicate which 'bug' would subsequently light up, but that they were not allowed to look at/pick up the 'bug' until it turned green. Following cue presentation there was a temporal gap ranging from 500-1300ms after which the 'bug' which had been previously cued, turned green and the child reached to grab is "as quickly as possible". Each cueing condition consisted of a combination of trials with different temporal gaps, which were balanced across cueing conditions. Introducing a variable temporal gap between cue and target presentation removed any degree of anticipation in movements towards target location and provided the opportunity to analyse the data in terms of interval between cue and target. No invalid cues were used.

All participants completed a form and motion coherence task, which involved a two forced choice task, where they were presented with a display of random elements and required to indicate the location of a circular feature on the computer screen (left or right). The form coherence task required detecting a circular area of concentrically aligned line segments in a background of randomly aligned line segments and the stimuli were identical to those used by O'Brien et al. (2002). The motion coherence stimuli were a revised version of the test but still required detecting signal dots which moved concentrically in a background of randomly moving noise dots. The percentage of concentrically moving dots or aligned lines was progressively reduced using a two-up, one-down staircase (for technical details refer to Braddick et al., 2000). This provided a threshold level at which a participant can discriminate form and motion, i.e. form and motion coherence.

Data analysis

Trials were excluded if fixation was not established directly before cue and target presentation or an anticipatory movement was made (<80ms for eye onset and <100ms for hand onset). Using a frame-by-frame analysis of the video data, the onset of eye movements following target presentation was determined by coding when the eye departed from fixation and continued to move for two frames or more. The hand movement data were filtered using an optimised

Woltring filter and then analysed using MatLab routines. Onset and landing times of the hand were determined from velocity curves. The time point at which velocity departed from zero (>3% max vel) or returned to zero (<3% max vel) was identified and checked by eye to avoid the localisation of any spurious jitters.

In addition to response times we calculated average velocity, in place of movement time (as targets were at differing distances from the hand start point) and three other kinematic variables to assess the efficacy of the initial pre-planned (ballistic) movement: (1) the heading error after 200ms; (2) The heading error at peak velocity and; (3) the number of trajectory adjustments during the acceleration and the deceleration phase. Heading error is a simple measure of deviation between an ideal heading (straight line between start point and target) and actual heading. This is first estimated 200ms after the start of the movement to reflect the initial programmed direction and then at peak velocity as a more robust estimate of the predominant movement direction, but that may include some rapid corrections. The number of trajectory adjustments reflects the efficacy of the direction and amplitude coding in that a perfectly programmed movement would require no later adjustments. Adjustments of the hand trajectory defined as secondary peaks in velocity (zero-crossing of acceleration) during the acceleration and the deceleration phase. Each re-acceleration and deceleration (2 zero-crossings, 1 secondary peak) was coded as a single adjustment. Finally because we have eye onset and hand onset times we calculated eye-hand lead as an additional measure of hand movement latency.

A percent improvement statistic was calculated in order to determine the advantage provided by a cue whilst removing any advantage the TD individuals have due to faster execution of movement. This was calculated for each cueing condition by taking the performance at baseline and weighting everything else relative to that, for each dependent variable (DV): ((DV value with a cue – DV value with no cue)/ (DV value with no cue)) x 100. A positive value indicated an improvement in performance (for that DV) compared to no cue trials and a negative value indicated a decrease in performance compared to no cue trials.

Statistical analysis

When considering percent improvement scores four independent variables were considered: *cueing condition* (static peripheral, static central, predictive motion 4 targets and predictive motion 12 targets); *cue type* (for static cueing, full and partial and for predictive motion, 6, 4 and 2); *group* (TD vs. DCD); and *age group* (primary group vs. secondary plus group). Each cueing condition was considered separately using 3-way ANOVA (cue type x group x age group). The imbalance of gender across the DCD population means that we do not consider gender differences. When simple main effects are reported Pillai's trace is reported and Bonferroni correction employed. Effect size (partial-eta squared, η^2, equivalent to r^2, (Field, 2006), is reported for all significant results and quantifies the magnitude of an observed effect. Cohen (1992) reported a small effect size is indicated by r^2=0.01, a medium effect size by r^2=0.09 and a large effect size by r^2=0.25.

Results

Form and Motion Coherence

A comparison of the threshold level on the form and motion coherence task was carried out between the TD individuals and the individuals with DCD, two independent 2 x 2 ANOVA (group x age group) were used to consider form and motion coherence seperately. A main effect of age group was found for both the form coherence task and the motion coherence task, whereby the older participants show lower threshold levels compared to younger participants [form $F(1,42)=8.65$ $p=.005$ $\eta^2=.17$, motion $F(1,42)=17.40$ $p<.001$ $\eta^2=.29$]. No difference was seen between groups on either the form or the motion task, therefore, unlike O'Brien et al. (2002) we found no evidence of processing differences between the control group and the DCD group. In order to determine whether the individuals with DCD displayed a specific deficit in the motion coherence task as compared to the form coherence task (or vice versa) we calculated the ratio between the threshold score of an individual with DCD and the threshold score of their age-matched control. This provided a 'deficit score' for the individuals with DCD on both the form and motion tasks which allowed us to directly compare performance across tasks. A 2 x 2 mixed ANOVA (age group x task, form vs motion) found no effect of task [$F<1$] indicating that the 'deficit score' was no different across the two tasks. If a participant with DCD showed an equivalent coherence score to their typically developing counterpart then the deficit score of that DCD participant would equal a value of 1. The deficit scores of the DCD group were found to not differ significantly from a value of 1 for either the form or the motion task [$t<1$, $p>0.05$; as illustrated with one-sample t-test with a test value of 1]. This illustrates that the participants with DCD obtained thresholds identical to their matched controls; therefore, the participants with DCD in this study do not show a specific deficit in either form or motion coherence

<u>Performance on all trials</u>

First we checked whether movement extent may have affected responses (Schellekens, Huizing, & Kalverboer, 1986; Van Dellen & Geuze, 1990). The distance of all targets for the gaze fixation point is equivalent, but the upper targets are farther from the hand start position than the lower targets, so we compared eye onset times and hand onset times for the upper and lower targets. We found no effect of target distance on either hand or eye onset times in addition we found no interaction between target distance and group [$p>.05$]. On this basis we combined data from all targets and used these to look at the performance on no cue and cue trials.

Performance on no cue trials

Before assessing the ability of participants to use advance pre-cue information we considered motor performance across group and age group when there was no advance cue; see Table 2 for no cue trial data. In order to check for fatigue effects we compared performance across the four blocks of no cue trials. A difference across these blocks was seen for heading error at maximum velocity [$F(3,132)=3.84$ $p=.011$ $\eta^2=.08$] whereby heading error decreased across the no cue blocks, from ~14^o to ~ 4^o in the TD group and from ~39^o to ~20^o in the DCD group. No other variables showed a difference across blocks of no cue trials. In addition, no interactions were seen, suggesting that this improvement in movement accuracy across blocks of trials was equivalent for both groups. The implications of this are addressed in the discussion.

Comparing group and age group performance across no cue trials we found no difference in eye onset time, hand onset time, movement time or average velocity. So the individuals with DCD were as quick to respond and as quick to complete the movement as the TD group and the young participants were as quick as the older participants[1]. A main effect of group and age group was

[1] The saccade onset latencies are quite long for all children, although the standard deviations are relatively small. It should be noted that this was not a simple saccadic task but required saccades to an unpredictable 4-choice peripheral array. Rolfs & Vitu (2007) used similar target arrays for a saccadic task with adults and reported mean saccade latencies of up to 340ms with but some trial latencies above 400ms. The latencies we report are consistent with this and what we have observed in children on other tasks (Wilmut, Wann, & Brown, 2006).

seen for heading error at maximum velocity [group $F(1,44)=13.77$ $p=.001$ $\eta^2=.25$ and age group $F(1,42)=4.98$ $p=.031$ $\eta^2=.11$] and a main effect of group was seen for the number of adjustments during the deceleration period [$F(1,44)=11.58$ $p=.001$ $\eta^2=.22$]. The effect of group illustrates that the TD individuals showed lower heading error and number of adjustments compared to individuals with DCD. The groups displayed equivalent heading error at initiation of movement (200ms after onset; TD ~24^o, DCD ~25^o), but the TD group showed a marked reduction by the time of maximum velocity (~8.2^o), no such reduction was seen in the DCD group (~23^o). This is supported by simple main effects which found an effect of time (initial vs. max velocity) for the TD group [$F(1,42)=9.59$ $p<.001$ $\eta^2=.14$] but not the DCD group. This is commensurate with the greater number of adjustments that occurred during the deceleration phase for individuals with DCD (Table 2). The effect of age group indicates that the younger participants showed a higher heading error at maximum velocity compared to the older participants, illustrating a developmental trend towards a more sophisticated movement system.

INSERT TABLE 2 HERE

Percent improvement during cue trials

When considering eye onset time (see Table 3) we found no main effect of cue type, suggesting no change in the eye onset time as cue information increased. We also found that percent improvement eye onset times were equivalent in the TD group and the DCD group. These results do not mean that there was no absolute difference in these variables across groups, but that once the difference between groups on the no cue condition was factored out, no additional group differences are seen. The lack of difference in the simple gaze response will be contrasted in the discussion with the differences observed in hand movements and eye-hand lead time.

INSERT TABLE 3 HERE

Hand movements

Using percent improvement, no change in time to peak velocity, time to peak acceleration, or the number of adjustments to the hand trajectory prior to landing, were seen across cueing conditions, groups or age groups. However, we did observe differences in response time, response speed and directionally accuracy. Because our primary interest is the advantage gained by different cue conditions, and all our measures were on a similar percent-improvement scale (see methods) we calculated an average percent improvement score across these three key variables; response time (hand onset), response speed (average velocity) and directional error (heading error 200ms after onset). This produces a much more concise set of results to test the cue-effect. The combination of these three factors can be thought of as a general measure of the ballistic part of reaching and how well a movement is initially programmed. They all reflect the planning of a movement and in combination we would expect these to reflect the use of pre-cueing information for movement organisation. In the case of hand onset time and heading error, a decrease in value indicates an improved performance; in speed the opposite is true. To standardise this percent improvement was inverted for average velocity. The result is illustrated graphically in Figure 2 (for individual kinematic variables see Table 3, for individual analyses see Appendix I). Analysing this composite hand movement measure found no interactions, however, main effects of cue type and group were found for all cueing conditions. Static peripheral [cue type $F(1,42)=27.03$ $p<.001$ $\eta^2=.39$; group $F(1,42)=15.78$ $p<.001$ $\eta^2=.27$]. Static central [cue type $F(1,42)=43.13$ $p<.001$ $\eta^2=.51$; group $F(1,42)=24.48$ $p<.001$ $\eta^2=.37$]. Predictive motion 4 target [cue type $F(2,84)=8.24$ $p<.001$ $\eta^2=.16$; group $F(1,42)=17.51$ $p<.001$ $\eta^2=.29$]. Predictive motion 12 target [cue type $F(2,84)=19.74$ $p<.001$ $\eta^2=.32$; group $F(1,42)=18.5$ $p<.001$ $\eta^2=.30$]. The predictive motion effect was due to a higher percent improvement for the duration and extent of the motion cue, i.e. 6dots (600ms) > 4dots (400ms) > 2dots (200ms); $p<.05$ (Bonferroni corrected). These findings illustrate that for all cueing conditions and across both groups, an increase in the amount of cue information led to an increase in the improvement seen in hand movement measure. The TD individuals show a greater improvement in the hand movement measure compared to individuals with DCD. To support the finding of a marked difference between the TD and the DCD participants we looked at the 95% confidence intervals for each group across all cueing conditions and cue types. In every case the confidence interval range of the DCD group fell outside the confidence interval range of the TD group. No age-related differences were found.

INSERT FIGURE 2 HERE

To determine whether the individuals with DCD had shown any improvement when presented with cues we used one-sample t-tests to compare the percent improvement score against zero (to minimise the number of comparisons and as no age-related differences had been found age groups were averaged together). Only three points were shown to be different from zero, these were: static peripheral with full cue [$t(22)=5.52$ $p=.001$]; static central with full cue [$t(22)=4.51$ $p=.001$]; and the predictive motion 4 target with 6 dots [$t(22)=3.19$ $p=.04$]. P values given are adjusted for multiple t-tests; this adjustment did not alter the outcome of the results. These results indicate that for full cue conditions the individuals with DCD do show an improvement in the composite hand movement score, however, no improvement is seen when presented with a partial cue, when presented with limited predictive motion cue information or when 12 targets are present. We carried out similar t-tests for the TD individuals, all points were found to be significantly greater than zero [$p<.001$]. This shows that in nearly all cases the TD group showed a significant improvement when presented with a pre-cue. P values given are adjusted for multiple t-tests; this adjustment this adjustment did not alter the outcome of the results.

Changes in Eye-Hand Lead with cueing

As outlined in the introduction, the difference between the onset of a saccade and the onset of a hand movement to a target allows us to assess whether differences in hand onset are attributable to a general slowness in orienting to the target. In addition, it can inform us on how a hand movement is planned: a large eye-hand lead could allow fixation of the target prior to initiation of a hand movement thus allowing the mover to utilise gaze position information in the planning of a hand movement; a small eye-hand lead (~100ms) is unlikely to serve this purpose and is indicative of a hand movement being planned predominantly using target information gleaned through peripheral vision prior to saccade initiation. We calculated eye-hand lead times by subtracting onset time of the eye from onset time of the hand to give a value of eye-hand lead; this can be found in Figure 3. We did not consider percent improvement in eye-hand lead for two reasons. Firstly, the absolute value of eye-hand lead is important in deciding the information an advance saccade might furnish. Secondly, because lead times can be quite low (i.e. zero is synchronous onset), then percentage calculations can be misleading: a change in eye-hand lead from 40ms to 100ms (150%) is unlikely to have major implications for the programming of the hand movement whereas a change from 120ms to 300ms (150%) would suggest a greater reliance on target fixation prior to hand initiation.

A cue type x group interaction was found for the static central [$F(2,84)=5.57$ $p=.005$ $\eta^2=.12$] and predictive motion 4 target condition [$F(3,126)=3.12$ $p=.029$ $\eta^2=.07$]. In order to discover if the eye-hand lead decreased across cue type for both groups simple main effects were used to compare cue type for each group. The TD group showed a significant effect of cue type for all cueing conditions [static peripheral $F(2,43)=17.76$ $p<.001$ $\eta^2=.38$, static central $F(2,43)=15.5$ $p<.001$ $\eta^2=.419$, predictive motion 4 targets $F(3,42)=17.41$ $p<.001$ $\eta^2=.55$ and predictive motion 12 targets $F(3,42)=7.92$ $p<.001$ $\eta^2=.36$]. In contrast the individuals with DCD only showed a decrease in eye-hand lead for the central peripheral condition [$F(2,43)=3.27$ $p=.048$ $\eta^2=.14$]. In addition, a main effect of group and cue type was found for all cueing conditions: static peripheral [group $F(1,42)=15.43$ $p<.001$ $\eta^2=.27$, cue type, $F(2, 84)=4.55$ $p=.013$ $\eta^2=.10$]; static central [group, $F(1,42)=6.87$ $p=.012$ $\eta^2=.14$, cue type, $F(2,84)=11.99$ $p<.001$ $\eta^2=.22$]; predictive motion 4 target [group, $F(1,42)=4.50$ $p=.04$ $\eta^2=.10$, cue type, $F(3,126)=25.62$ $p<.001$ $\eta^2=.38$]; and predictive motion 12 target condition [group, $F(1,42)=4.80$ $p=.034$ $\eta^2=.10$, cue type, $F(3,126)=9.18$ $p<.001$ $\eta^2=.18$]. These results indicate that for all cueing conditions the TD individuals showed a lower eye-hand lead compared to individuals with DCD. Again no age-related differences were found.

INSERT FIGURE 3 HERE

Long vs. short inter-stimulus intervals

Up to this point in the analysis it does not appear that individuals with DCD are using the motion pre-cue information. One possible explanation, however, is that they are sensitive to the motion cueing but that they require longer to process and incorporate this information into the preparation of an appropriate response. Within our design we had a variable inter-stimulus interval (ISI) between the delivery of the cue and the appearance of the target (signal to move) of 500-1300ms. We therefore had the ability to examine a hypothesis of a processing delay in DCD. We divided trials in the predictive motion conditions into short (500-900ms) and long ISI's (901-1300ms) and re-visited the hand movement measure score, comparing percent improvement scores during long and short ISI's (Figure 4)[2]. A four-way ANOVA (group x age group x cue type x ISI) was conducted. For both cueing conditions a group x ISI interaction was found [predictive motion 4 target $F(1,42)=10.38$ $p=.002$ $\eta^2=.19$, predictive motion 12 target $F(1,42)=12.77$ $p<.001$ $\eta^2=.23$], simple main effects comparing ISI across group revealed an effect of ISI for the DCD group [predictive motion 4 target $F(1,42)=41.05$ $p<.001$ $\eta^2=.49$, predictive motion 12 target $F(1,42)=48.38$ $p<.001$ $\eta^2=.54$] but not the TD group. These results suggest that the DCD group show an advantage to pre-cue information when the gap between cue and target is approximately 1 second. No other interactions were found.

To confirm that the individuals with DCD showed an advantage when presented with long ISI's we compared the percent improvement score for the short and long ISI's to zero. No percent improvement scores were seen to differ from zero for the short ISI's [$p>0.05$]. In contrast, for the

[2] For the static cueing condition the lack of an advantage to a partial cue in children with DCD has been attributed to the high cost of generating a movement to an incorrect target location (Mon-Williams et al., 2005). An elongated ISI would not serve to offset this. If the problem in using predictive motion is processing and extrapolating motion direction then the length of the ISI may well be the cogent variable.

long ISI's percent improvement scores were seen to be greater than zero for the predictive motion 4 targets for 6 cues [t(22)=4.84 p=.001] and 4 cues [t(22)=4.83 p=.001] and on the predictive motion 12 target for 6 cues [t(22)=4.34 p=.001] (p values adjusted for multiple comparisons). This confirms that the individuals with DCD can use predictive motion cues to pre-program movements but that this is only apparent when a longer temporal gap is given between cue offset and target onset. This compliments the lack of a difference between the groups on the previous form and motion tasks and suggests that individuals with DCD are sensitive to this type of information. Similar t-tests were run on the data from the TD group. For both long and short ISI's TD individuals showed a percentage improvement scores significantly greater than zero [p<.001, values given are adjusted for multiple t-tests], indicating an advantage to pre-cues in both long and short ISI's.

INSERT FIGURE 4 HERE

Discussion

It is often reported that children with DCD are slower and less accurate in their manual responses. It seems that the process of generating and controlling a manual movement is less refined, but the locus of the problem has not been established. For a task requiring a speeded response (typical of those used in previous research) children with DCD could experience difficulty with the rapid deployment of attention, such a deficit would certainly be in line with a per-motor theory of dynamic attention (Rizzolatti et al, 1987). Following this thread, children with DCD could have problems in allocating covert attention prior to a movement response (e.g. in pre-cue trials) or initiating overt attentional (gaze) shifts as a precursor to manual responses.

To date no-one has excluded this possibility in DCD and there is evidence that this group of children can have problems with attentional disengagement (Wilmut, Brown, & Wann, 2007). In this study we started with a very simple manual task: one of 4 toy bugs was illuminated and participants had to grab that bug as quickly as possible. In these circumstances we found that individuals with DCD were not slower to initiate an eye movement to the target in either the conditions where there was a pre-cue (initial covert orienting) or no pre-cue. This would seem to exclude the dynamic allocation of attention as a source of the problem in children with DCD.

We also found that, in the response without pre-cues, individuals with DCD could initiate fast grasping responses as well as TD individuals (movement time, movement speed and initial directional error were equivalent between the two groups). One interesting difference, however, was that the TD group were able to reduce initial heading error of ~24 ^{o}, to less than 10 ^{o} by the time they had reached peak velocity of the movement. In contrast, the DCD group relied upon a greater number of end point corrections to compensate for an inaccurate initial heading error. This may lead to much slower movements if there was an increase in the precision requirements for the grasp. So at one level individuals with DCD may produce slower manual responses because of their inability to introduce on-line trajectory corrections and their reliance upon end-point corrections. This problem with on-line control seems uncontroversial, but to our knowledge this has not been demonstrated previously.

Another reason why more complex movements may be slowed, however, might be the preparation phase of a movement where direction and extent are parameterised prior to execution, and this was the primary aim of introducing the pre-cue conditions.

Cueing location with static stimuli

Both the TD individuals and the individuals with DCD show an advantage when presented with static unambiguous pre-cues, informing them in advance which target will be highlighted and this has been shown previously (Mon-Williams et al., 2005). In this experiment the advantage for pre-cue information was reflected in terms of a decrease in hand onset time and an increase in average velocity. There was also a reduction in the initial heading error (200ms post movement onset) illustrating more accurate parameterisation of the initial movement. The lack of any differences between groups in eye-movement onsets would seem to exclude an explanation based on the allocation of attention in response to partial or full pre-cues. The calculation of eye-hand lead provides an estimate of delays to hand initiation over and above any differences in the gaze response and as the level of pre-cue information increased. We might expect this measure to directly reflect the advanced parameterization of the hand movement, in that a hand trajectory that is pre-specified during the pre-cue period can be initiated very rapidly as soon at the final target is revealed (low eye-hand lead) whereas a hand trajectory that is only specified once the final target is revealed will result in an elongated eye-hand lead. On the no cue trials the onset of the hand followed the onset of the eye by some 400ms (Figure 3), by which time the target was fixated and ocular coordinate information would be available. In the TD group, when a clear pre-cue was provided it can be seen that the hand movement followed the eye by less than 100ms. This reduction of ~300ms is well above any sampling error in estimating the lead time (±17ms) and suggests a switch in the mode of control and a move towards pre-parameterization of the hand movement on the basis of the pre-cue. There was an interaction, however, because the DCD group did not reduce their eye-hand lead time to any great degree and we must presume that they continued to rely upon target fixation for a significant part of their movement preparation process (Figure 3).

A clear difference between the two groups was that the TD individuals showed an advantage when presented with partial cues. In contrast, the individuals with DCD show no advantage when presented with partial cues, again this has been shown previously (Mon-Williams et al., 2005). Dwelling once again on the issue of eye-hand lead, it is remarkable that with partial static cues (left/right) TD individuals were able to reduce their eye-hand lead to less than 200ms. This is at the fringe of what might be considered a useful lead-time for providing information from fixation prior to hand initiation. It may be that in the partial cue conditions the eye movement assists a partially prepared movement by providing the information for the early directional corrections that we observed in the TD hand trajectories, but not in the DCD hand trajectories. Advance information allows the participant to plan a movement before a response is required (Mon-Williams et al., 2005) and partial or ambiguous advance information allows the preparation of an incomplete movement which then needs to be updated online. Previous research has indicated that children with DCD find it hard to modify a planned movement compared to TD children (Mandich et al., 2003). Mon-Williams et al. (2005) suggest that children with DCD find the cost of executing an incomplete movement and updating online too high in comparison to the benefits of planning and executing a movement early. The results from this experiment are consistent with these conclusions.

<u>Cueing location with predictive motion</u>

When presented with predictive motion cues the TD individuals show an advantage with moving dot cues lasting for 200, 400 and 600ms, with both 4 and 12 potential targets. Again the advantage seen was in terms of a decrease in hand onset time, an increase in average velocity and a decrease in the initial direction error of the hand. As with the static cues the predictive motion allowed the TD individuals to reduce their eye-hand lead time from ~400ms to ~200ms, with 2 dot (200ms) predictive motion, and to less than 100ms, with 6 dot (600ms) predictive motion (Figure 3). In contrast, the individuals with DCD only showed an advantage to 6 dots in the predictive motion 4 target cueing condition and they showed no advantage when presented with fewer cues or when more targets were present. This finding may not be that distinct from that found with central static cues. Shulman et al. (1999) provided evidence that a static directional cue can activate motion sensitive brain regions. So a 600ms central arrow shares some processing mechanisms with a 600ms dot-motion display.

Why do individuals with DCD have difficulty in using predictive motion cues that provide a clear advance to the TD group? Our analysis of the no-cue blocks confirmed that this is not a fatigue effect; in fact there was a minor improvement in performance for both groups as the experiment progressed. In addition, the variables that reflected the differences between groups for motion cueing did not in fact change across the no-cue blocks. When we considered the responses to partial static cues we presented the hypothesis that individuals with DCD refrained from paramertizing a generalised movement which required subsequent updating. Because the motion cues were not ambiguous this explanation does not fit so well to a difficulty using predictive motion cues. The DCD group failed to show an advantage to 200ms or 400ms of motion, towards one of 4 targets, placed at 90^{o} intervals. These cues would only be ambiguous if the direction of motion was not adequately processed. The DCD group also failed to show an advantage of any predictive motion (200-600ms) towards one of 12 targets. With a larger number of targets an individual may mis-perceive the target that was being cued, initiate a slightly mis-directed response and have to correct it. This may well impact on the general measures of response speed and accuracy of initial heading but the lack of any improvement as the cue-motion duration became longer, and therefore more specific, again suggests a difficulty in processing the motion cues rather than a more general compensation for uncertainty.

Given the argument above we could put forward a hypothesis of a general motion-processing problem. But we found no evidence that the individuals with DCD have impaired ventral or dorsal stream function using form and motion coherence tests. This contrasts with the finding that children with developmental Dyspraxia have selective impairment to dorsal stream function (Stein & Walsh, 1997), or the contrary finding that children with Dyspraxia have selective impaired ventral stream function (O'Brien et al., 2002), or the more general finding that 'clumsy' children have both impaired dorsal and ventral function (Sigmundsson et al., 2003). There are two explanations for these contrasting findings: firstly, the differences in group selection across studies is large, differences in assessment of children with Dyspraxia and individuals with DCD could explain the different results; secondly, differences in previous results could be explained if only subgroups of children or adults show impairments in dorsal or ventral streams. This is supported by evidence that dorsal stream impairment is seen in some TD children (Gunn et al., 2002). In the present experiment, none of the individuals with DCD showed impairment in either the dorsal or the ventral stream[3]. We did find a significant improvement in thresholds with age,

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[3] None of the participants with DCD fell outside the confidence intervals of the TD group (confidence intervals were calculated separately for the primary and secondary age group due to the age difference seen in thresholds).

confirming our procedures were sensitive, and extraneous factors such as greater distractibility or impulsivity in the DCD group would lead to a higher number of errors (higher threshold), not an equivalent threshold. In this respect we consider the finding of no difference as robust and this suggests that a global motion processing is not the primary cause of deficits seen in the use of predictive motion cues in individuals with DCD. It is possible that a local-processing deficit (not tested using form and motion coherence thresholds) would be sufficient to account for these specific deficits. But given that the problems are reduced when ISI is increased, we would argue, that neither a local nor a global processing deficit is a parsimonious account of the problems observed in using motion cues. A further factor to consider is that no differences were observed between groups in their saccadic response time, which suggests that the acuity of motion processing was sufficient to process a directional saccade in the DCD group but did not support the efficient organisation of a hand movement.

When we divided the inter-stimulus intervals (ISI: gap between the offset of the cue and onset of the target) into short and long intervals, we saw that individuals with DCD did start to show an advantage to predictive motion cues with long ISI's. This finding does seem to suggest that the children with DCD take longer after presentation of a cue to process directional motion and set up parameters for a hand movement. Because eye-movements were not delayed this would seem to exclude the suggestion that individuals with DCD are slow at processing direction of motion from brief (200-400ms) stimuli. Eye-movement initiation is a highly efficient encapsulated system where an initial saccade to a peripheral location is often followed by a corrective saccade. In contrast, ballistic hand movements are high energetic cost and effective control equates a smooth accurate trajectory with minimum corrections. We observed in the no-cue trials that individuals with DCD were more erratic in their initial direction of movement trajectories and had to make more late corrections to the hand trajectory. This then seems to be compounded by difficulty in extrapolating from motion stimuli to coordinate information that they can use to organise a hand movement. The ISI finding seems to suggest that they may be able to do this given a longer movement (~1sec), but they have difficulty in using predictive motion cues in a rapid task requiring a shorter preparation time. Unfortunately many natural motion stimuli, such as flying balls, falling cups or wobbling bicycles often require a rapid directional hand movement.

Similarly to Olivier et al., (1998) and Olivier & Bard (2000) we found no age-related advantage in the TD group in terms of percent improvement, so the advantage to pre-cue information is equivalent in the primary school group and the secondary school plus group. This was an effect reflected in the DCD group, suggesting that an adult with DCD shows the same level of advantage to pre-cue information as a six year-old child with DCD. It could be argued, however, that the lack of difference was caused by the classification of individuals in the older group. The older group were classified as DCD on their performance for age band 4 of the MABC (designed for 11-12 year-olds). As the older group was largely over 12 years of age these individuals were performing badly on a test designed for younger children which may indicate a higher level of impairment; which could be used to explain the lack of age-related differences. Only a small gain in performance is seen after 10 or 12 years of age for many manual tasks (Annett, 1970; Schulman et al., 1969), so although the lack of any age-related differences may be explained in terms of impairment level, it seems more likely that age did not impact on the ability to use the advance information provided in these tasks. Whether this generalises to age having no effect on the utilisation of advance information is not clear.

In summary, this study has shown that typically developing individuals as young as 6 years of age can program movements in advance using both static and predictive motion cues. In contrast, we have shown that the individuals with DCD display little advantage in movement organisation when presented with predictive motion cues, but they can begin to show some benefit when given a longer processing time. We have excluded the dynamic allocation of attention as a causal factor and have proposed a problem occurs in the translation of brief motion stimuli to coordinates that can be used to organise gross motor responses. In the natural context of the playground or high-street, we are surrounded with predictive motion cues. Balls roll, pedestrians veer, cyclists and cars approach. We have used a relatively abstract, desktop task, to allow tight experimental control, but if the results on motion pre-cues can be confirmed across other tasks the impact could be considerable. Being slow in parameterizing a movement on the basis of predictive motion in an everyday setting can result in objects crashing to the floor, bumping into other pedestrians, or being slow to respond to an approaching vehicle. It is an aspect or everyday control that warrants further investigation.

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Appendix I

Additional analyses were carried out on the components of the hand movement measure (hand onset, average velocity and heading error at 200ms) for percentage improved values of these see Table 3.

For *hand onset* a main effect of cue and group was found for, static peripheral cueing [cue, $F(1,42)=16.97$ $p<.001$ $\eta^2=.22$, group $F(1,42)=4.64$ $p=.037$ $\eta^2=.10$], static central cueing [cue, $F(1,42)=13.34$ $p=.001$ $\eta^2=.24$, group, $F(1,42)=13.75$ $p=.001$ $\eta^2=.25$], predictive motion 4 target cueing [cue, $F(2,84)=20.69$ $p<.001$ $\eta^2=.33$, group, $F(142)=15.12$ $p<.001$ $\eta^2=.26$] and predictive motion 12 target cueing [cue, $F(2,84)=12.71$ $p<.001$ $\eta^2=.23$, group, $F(1,42)=18.18$ $p<.001$ $\eta^2=.30$].

For *average velocity* a main effect of cue was found for, static peripheral cueing [$F(1,42)=36.42$ $p<.001$ $\eta^2=.46$], static central cueing [$F(1,42)=6.28$ $p=.016$ $\eta^2=.130$], predictive motion 4 target cueing [$F(2,84)=2.53$ $p=.086$ $\eta^2=.057$] and predictive motion 12 target cueing [$F(2,84)=1.69$ $p=.191$]. No effects of groups were found.

For *heading error* 200ms after hand onset the results were as follows: static peripheral cueing [group, $F(1,42)=10.18$ $p=.003$ $\eta^2=.19$, no effect of cue]; static central cueing [cue, $F(1,42)=34.49$ $p<.001$ $\eta^2=.45$, group, $F(1,42)=11.70$ $p=.001$ $\eta^2=.22$]; predictive motion 4 target cueing [group, $F(1,42)=10.67$ $p=.002$ $\eta^2=.20$, no effect of cue]; and predictive motion 12 target cueing [cue, $F(2,84)=6.24$ $p=.003$ $\eta^2=.13$, group, $F(1,42)=7.41$ $p=.009$ $\eta^2=.15$].

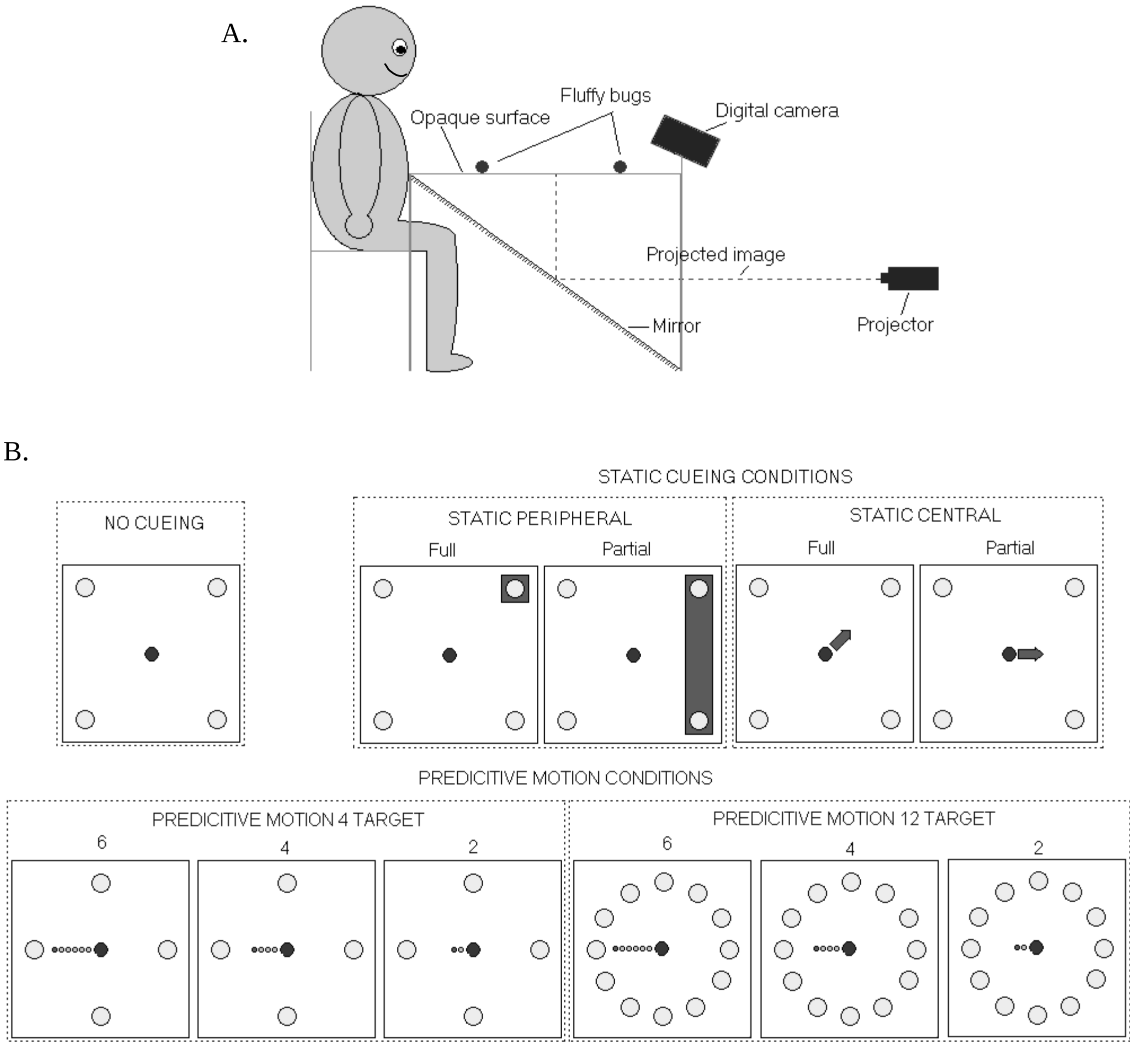

Figure 1. A: 2D illustration of the equipment setup. In this setup the four Vicon cameras are not illustrated, but they were placed around the participant in locations conducive to motion capture of the hand. B: Schematic illustration of target locations and cue types for the both the static and predictive motion conditions. The light grey circles represent the 'fluffy bugs' which remained on the table top throughout the experiment. The cues and the fixation spot were generated with the projector and so could be turned on and off. In the predictive motion conditions each dot was only even visible, for 100ms, in one position at a time.

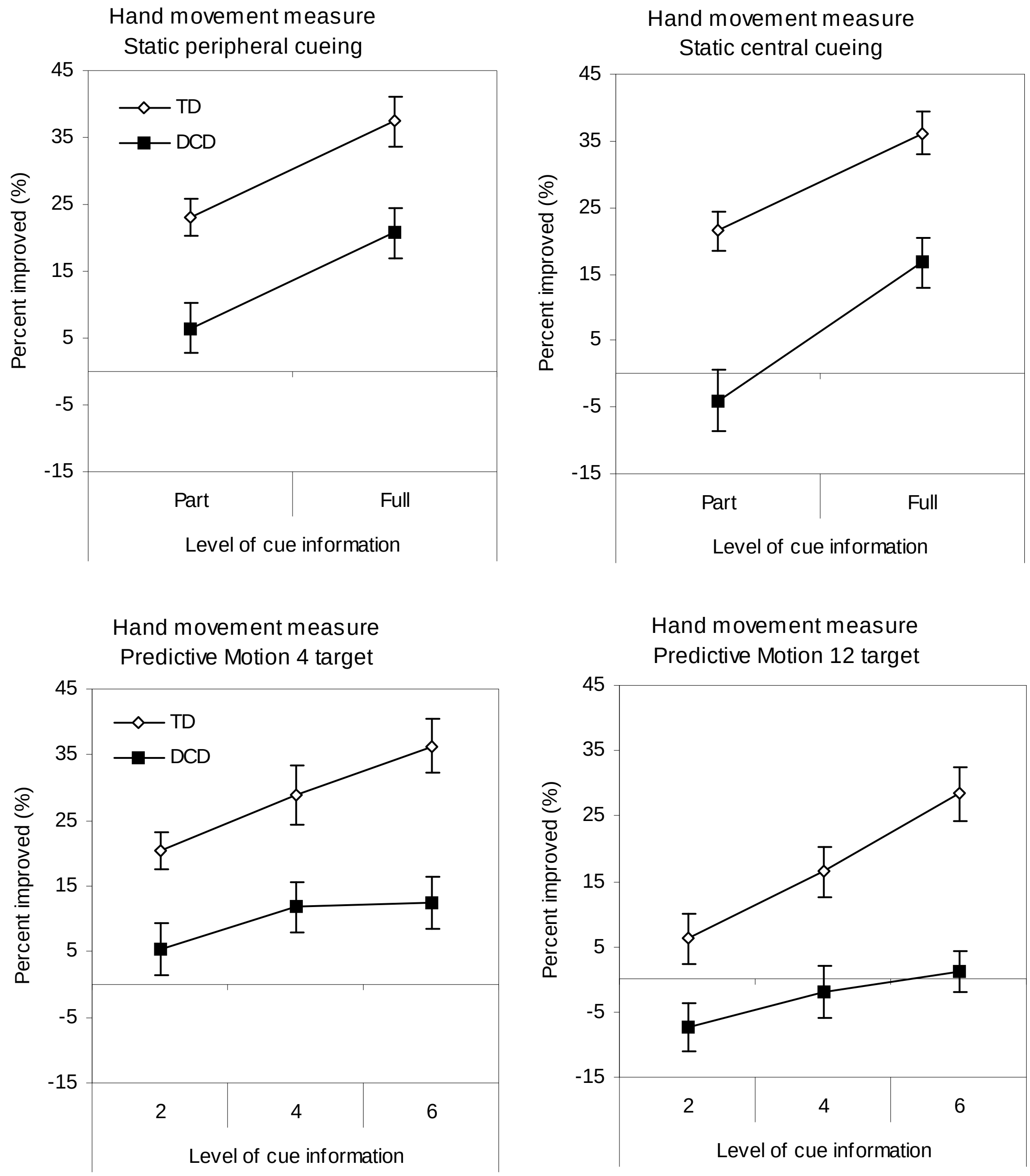

Figure 2. Graphs showing the percentage improvement of the hand movement measure (hand onset, average velocity and heading error at 200ms) for all cueing conditions and all cue types. The TD individuals are represented by hollow diamonds and the DCD individuals by filled squares. Data is collapsed across age as there were no effects of or interactions with age. Error bars represent standard error

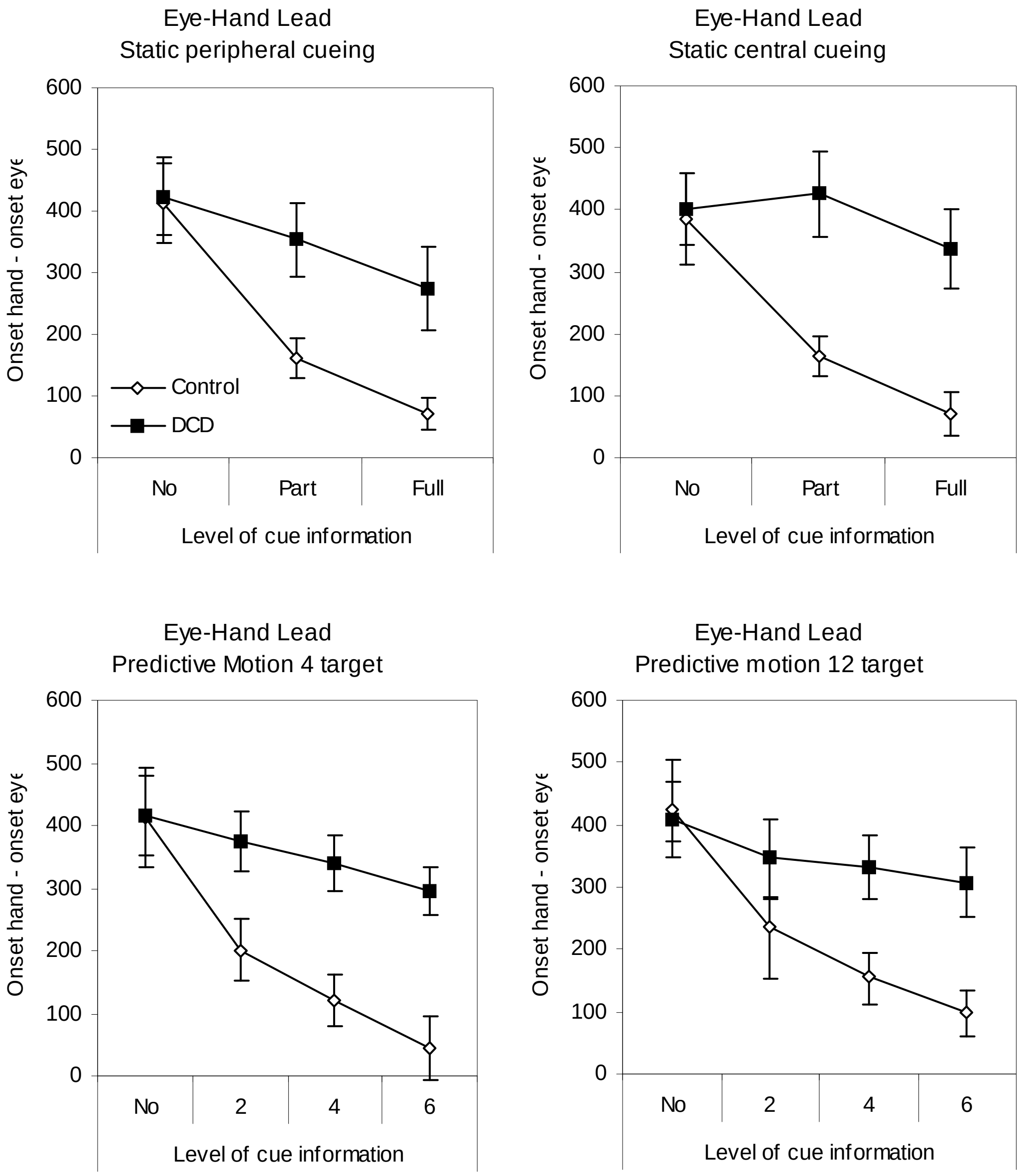

Figure 3. Graphs showing the eye-hand lead (onset time of the hand - onset time of the eye) for all cueing conditions and all cue types. As before the TD individuals are represented by hollow diamonds and the DCD individuals by filled squares. Data is collapsed across age as there were no effects of or interactions with age. Error bars represent standard error.

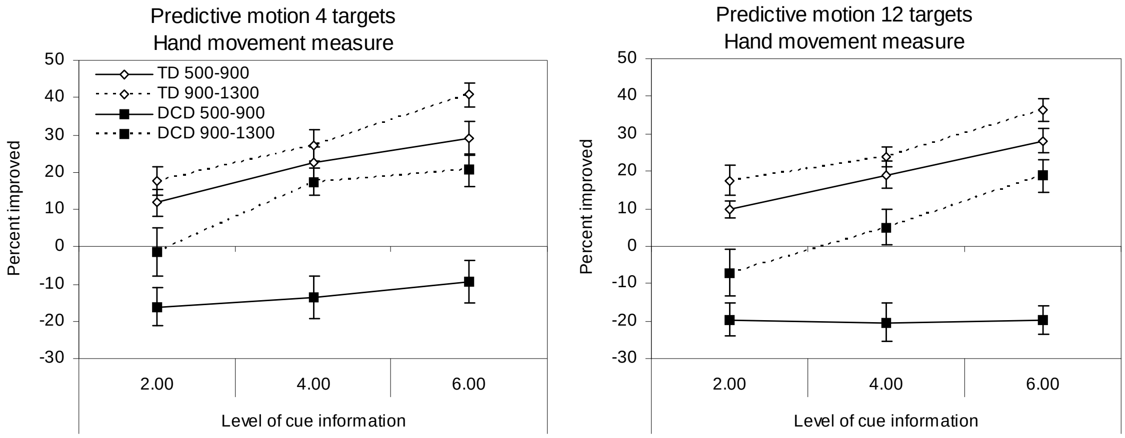

Figure 4. Graphs showing the composite movement score separated into short (500-900ms) and long (901-1300ms) inter-stimulus intervals. Data is collapsed across age. Given for the predictive motion cueing conditions only, short ISI's are represented by filled symbols and long ISI's are represented by hollow symbols. Error bars indicate standard error

Table 1. Details of the four different participant groups, includes age (range and mean age), average MABC centile (with a breakdown of the number of children falling below the 5th and between the 5th and 10th centiles), average IQ and gender ratio for all groups.

	Age group	N	Age		MABC percentile	Spread of MABC percentile scores (N)		IQ	Gender ratio (m:f)
			Range (years)	Average (yr.mo)		<5th	5th-10th		
TD	Primary school	11	6-12	9.6	53	N/A		103	4:7
	Secondary school*	12	13-23	16.4	39			109	6:6
DCD	Primary school	11	6-12	9.5	1.8	10	1	98	9:2
	Secondary school*	12	13-23	16.4	4.7	8	4	102	9:3

*For both groups the secondary school plus group included 6 participants between 13 years and 16 years and one 16 and 17 yr old participant, two 18 yr old participants and one 19 and 23 yr old participant

Table 2. Data for no cue trials. Includes hand onset time, average velocity, heading error (200ms after onset and at maximum velocity), and number of adjustments during the acceleration and deceleration phase of the movement. Standard deviation is in brackets.

		TD		DCD	
Eye onset (ms)		362	(87)	397	(83)
Hand onset (ms)		780	(321)	815	(216)
Average Velocity (ms^{-1})		0.49	(0.10)	0.48	(0.14)
Average movement time (ms)		722	(125)	710	(187)
Heading error (^{o})	200ms after onset	24.6	(12.1)	25.4	(9.8)
	At maximum velocity	8.15	(8.7)	23.1	(18.0)
Number of adjustments	Acceleration	0.08	(0.14)	0.16	(0.19)
	Deceleration	0.11	(0.10)	0.30	(0.18)

Table 3. Percentage improvement scores for eye onset (ms), hand onset (ms), average velocity (ms-[1]), and heading error at 200ms (°) is shown for all cueing conditions and both groups. Age group data is not provided as no differences were seen between the groups. Standard deviation is in brackets.

		Static cueing				Predictive motion cueing					
		Peripheral		Central		4 target			12 target		
		Part	Full	Part	Full	2	4	6	2	4	6
Eye onset	TD	-6.7 (28.9)	3.3 (25.6)	7.4 (21.2)	11.1 (19.2)	4.24 (27.9)	8.9 (28.8)	10.5 (20.9)	5.6 (32.7)	8.1 (31.2)	7.9 (28.9)
	DCD	-8.9 (25.5)	3.3 (27.1)	7.6 (22.3)	4.7 (27.9)	7.4 (28.8)	7.6 (25.9)	-8.3 (35.6)	0.02 (30.4)	3.6 (36.2)	5.2 (25.4)
Hand onset	TD	25.8 (27.0)	35.5 (24.7)	28.3 (23.5)	41.3 (21.6)	23.2 (20.9)	35.1 (21.1)	43.3 (18.4)	19.6 (17.7)	28.8 (20.4)	41.4 (19.4)
	DCD	8.4 (26.8)	22.2 (22.8)	4.5 (24.9)	20.6 (25.6)	1.1 (26.7)	16.4 (23.0)	23.3 (19.8)	-2.6 (33.5)	11.25 (19.5)	17.9 (26.3)
Average Velocity	TD	10.1 (22.4)	29.8 (31.9)	5.25 (19.3)	19.1 (23.6)	11.9 (19.5)	21.9 (43.2)	26.1 (28.1)	0.5 (19.8)	5.2 (27.9)	14.2 (27.2)
	DCD	3.7 (17.1)	27.4 (23.3)	-1.1 (18.8)	1.3 (23.8)	11.4 (27.5)	13.1 (26.6)	14.4 (18.9)	-0.1 (19.0)	-1.6 (23.0)	-2.9 (19.7)
Heading error at 200ms	TD	33.3 (30.0)	46.9 (33.7)	30.9 (29.7)	47.9 (20.3)	26.2 (33.8)	29.6 (31.9)	39.6 (32.5)	-1.3 (51.6)	29.6 (42.1)	26.2 (33.8)
	DCD	7.14 (47.6)	12.6 (41.7)	-15.4 (52.4)	28.2 (36.8)	3.9 (36.6)	5.75 (30.6)	-0.3 (59.5)	-19.2 (40.4)	-15.3 (37.9)	-11.1 (36.8)