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A test of motor (not executive) planning in developmental coordination disorder and autism

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ABSTRACT

Grip selection tasks have been used to test ‘planning’ in both autism and developmental coordination disorder (DCD). We differentiate between *motor* and *executive* planning and present a modified version of a motor planning task. Participants reached-and-grasped a cylinder in one of two orientations before turning it clockwise or anticlockwise. On half the trials, the turning action only resulted in a comfortable final posture at the cost of making a harder initial reach-to-grasp action; ending comfortably has been taken as the evidence of ‘planning’. We hypothesised that initial grip selection (easier or harder) would be dominated by motoric developmental status. Adults always selected an initial grip that resulted in a comfortable end-state when reaching with their dominant hand, but occasionally ended uncomfortably with their non-dominant hand. Most 9-14 year old children with and without autism also showed this ‘end state comfort’ bias, compared with only half of children aged 5-8 years. In contrast, children with developmental coordination disorder were biased towards selecting the simplest (minimal rotation) initial movement, even at the cost of end state comfort. Our results are best understood in terms of motor planning, with selection of an easier initial grip resulting from poor reach-to-grasp control rather than an executive planning deficit. The absence of differences between children with autism and controls may reflect the low demand this task actually places on executive planning abilities.

Motor planning

The topic of ‘planning’ has been of great interest in recent years, as people investigate proposed deficits in planning in various atypically developing populations. Planning skills are thought to be impaired in a range of neurodevelopmental disorders including attention deficit hyperactivity disorder (ADHD: e.g. Scheres, Oosterlaan, Guerts, Morein-Zamir, Meiran, Shut, Vlasveld & Sergeant, 2004), autism (e.g. Hill, 2004; Hughes, 1996) and developmental coordination disorder (DCD: cf. Smyth & Mason, 1997). But what exactly is ‘planning’?

Planning seems to fall naturally into two basic categories within the research literature. The first, which we will call *executive planning*, categorises planning as an executive function involving a sequence of choices or moves that must be arranged in order to achieve a desired end state (a goal). Methods for assessing executive planning include tasks such the Towers of Hanoi (e.g. Hill, 2004) and London (Shallice, 1982), or the Stockings of Cambridge (part of the computerised CANTAB battery). These tasks require a sequence of abstract thoughts about a goal state and place demands upon working memory. The second category focuses on what we shall refer to as *motor planning* (Cohen & Rosenbaum, 2004; Rosenbaum, Heugten, & Caldwell, 1996; Rosenbaum, Marchak, Barnes, Vaughn, Slotta, & Jorgensen, 1990; Rosenbaum, Meulenbroek & Vaughn, 1996; Rosenbaum, Vaughn, Barnes & Jorgensen, 1992; Rosenbaum, Vaughn, Jorgensen, Barnes & Stewart, 1993). Rosenbaum and colleagues have used tasks that measure the type of grip selected by participants (e.g. overhand versus underhand) when asked to do a two-stage task (e.g. grasp-and-turn). Adults in these tasks tend to make a less comfortable initial grasp if it allows them to turn the object so as to end up in a comfortable posture (referred to as the ‘*end state comfort effect*)’.

Motor planning

Motor planning and executive planning are often discussed as if they have a great deal in common (e.g. Rosenbaum, Carlson & Gilmore, 2001). Indeed, it is likely that many movement tasks require both executive and motor planning (what we might call *action planning*). Nonetheless, there are important differences between motor and executive planning that need to be addressed. For example, the Towers of Hanoi and London involve several abstract, largely non-repetitive, cognitive steps. These tests of executive planning often rely on the task being first performed in the imagination before commencement and depend upon executive processes such as working memory. In contrast, tasks that assess motor planning involve behaviour that is often cognitively impenetrable and depends upon learned movement skills built up over developmental experience. Conflating these two and referring simply to 'planning' has led to some confusion in the developmental literature.

Comment [ADW1]: We started calling it this in the ESRC grant and I like it, so I've changed this accordingly

For example, Smyth and Mason (1997) used Rosenbaum et al.'s handle task on children aged 4-8 years with and without DCD. They found that young children had a propensity to grasp the handle in a way that led to uncomfortable end states after rotation. This was interpreted as showing that the young children lacked 'planning' skills during the task. Hughes (1996) also administered a grip selection task, but this time to a group of children with autism. Hughes found children with autism were less likely to select a grip that favoured end-state comfort (the adult pattern observed by Rosenbaum et al) and used this finding to suggest that the children lacked 'planning' skills.

Motor planning

The difficulty with interpreting the results as generic planning difficulties is the lack of distinction between motor and executive planning. We suggest that grip selection tasks may be problematic as a test of executive planning and that interpreting the results of Hughes (1996) or Smyth and Mason (1997) in these terms (or generic ‘planning’ terms) is inherently unsatisfactory. Additionally, adults only selected a grip that results in end-state comfort on 80-90% of trials in two key handle locations (Rosenbaum et al 1993). If we interpret this as evidence of executive planning then we must suppose that the adults lost their ability to cognitively plan on 10-20% of the trials. This strange conclusion arises from assuming that the optimal solution to the problem is always the one selected by the majority and that any deviation implies impaired executive planning.

An alternative framework is to treat grip selection tasks as testing motor planning, with motor status affecting motor planning. Rosenbaum’s handle turning task has two requirements to reach the end state position: (1) reach-to-grasp the handle and (2) turn the handle. Selecting a grip to maximise end-state comfort is only efficient if this is not outweighed by the extra costs of a difficult initial movement. Children who find the initial reach-to-grasp difficult may select the simplest initial movement even at the cost of an overall inefficient movement. Likewise they might be biased to select a constant grip despite this being less optimal in the second task component (i.e. perseverate, as in the A-not-B error; Thelen, Schöner, Scheier & Smith, 2001). Selection of this constant grip might then be subject to other biases, such as trying to minimise the required pre-contact rotation of the arm. Thus, observation of one type of grip selection cannot be taken as evidence for or against executive planning per se.

Motor planning

If we accept that grip selection tasks primarily evaluate motor rather than executive planning then we can begin to consider what factors influence (‘bias’) motor planning. One possible bias is the previous movement. Repeating an action (perseveration or hysteresis) - can be easier and therefore more likely than generating a new one (e.g. Cohen & Rosenbaum, 2004; de Lussanet, Smeets & Brenner, 2001, 2002; Thelen et al, 2001; van Bergen, van Swieten, Williams & Mon-Williams, 2007). Two additional potential biases are: (1) pre-contact minimal rotation (MR; van Bergen et al, 2007) in which the hand is rotated through the minimum distance required to reach a final posture, resulting in an easier movement and (2) end-state comfort (ESC; e.g. Rosenbaum et al, 1990) in which initial comfort is sacrificed in order to achieve a comfortable final position. We therefore modified the task used by Smyth and Mason (1997) to expose the potential influence of grip selection biases in groups at different developmental stages. The crucial aspect of our design was that (1) and (2) were placed in direct opposition with one another so that selecting maximal pre-contact rotation would increase end-state comfort on half the trials (and vice versa).

These biases help constrain a task to make it solvable - we therefore predicted that their influence would vary as a function of motor developmental status or competence. Adults reaching with their preferred hand would always be biased by ESC, but might occasionally be biased by MR with their non-preferred hand. Young children are likely to select an easier initial movement (because they have less well developed prehension skills; Kuhtz-Buschbeck, Stolze, Johnk, Boczek-Funcke & Illert, 1998; Mon-Williams, Tresilian, Bell, Coppard, Nixdorf & Carson, 2005; Tresilian, Mon-Williams, Coppard & Carson, 2005) and so we predicted that young children would primarily show the MR bias. Children with DCD would be even more strongly biased by MR because of their fundamental difficulty with prehension. We also looked at grip selection in children with autism, as these children are known to have executive planning deficits (Hughes, Russell & Robbins, 1994); we predicted, however, on the basis of our current scheme, that this might not translate to a motor planning deficit. If any group showed any tendency to perseverate, this would also be clear in the current design.

METHODS & RESULTS: Executive planning in DCD

Children with autism are well known to have difficulties with tasks measuring cognitive planning (e.g. the Tower of Hanoi or London) and executive function (e.g. the Wisconsin Card Sorting task). However, we needed to establish whether children with DCD showed any difficulties on a test of executive level planning – we therefore tested a sample of 18 children with DCD (16 males, 2 female) aged 7-11, average age 9.91 years) on the Tower of London. For each child we computed their scaled score from the appropriate age tables in the NEPSY Manual (Korkman, Kirk & Kemp, 1998); these scaled scores have a mean of 10 and a standard deviation of 3. All of the children scored within or above 1SD from the mean (scores ranged from 8-16, mean = 11.83). There is therefore no evidence to suggest that children with DCD have any specific executive function difficulties in planning.

METHODS: Motor Planning

Participants

Motor planning

There were four groups of participants: children with DCD aged between 6 and 13 years; children with autism aged between 9 and 14 years; control children; and adults.

The first group consisted of 27 children (20 male) diagnosed with DCD by the DSM-IV criteria. The children were recruited from the Royal Aberdeen Children's Hospital (RACH). The children were diagnosed by a history of coordination problems and performance assessed as being below the 5th percentile on the Movement ABC (MABC: Henderson & Sugden, 1992) by occupational therapists. The DCD population were examined by the relevant clinical services within the RACH for signs of known neurological disease and autism (the presence of which would have prevented a diagnosis of DCD under DSM-IV criteria). Most (24/27) of the children with DCD were right handed as indexed by their writing hand. Their age ranged between 6 and 13 years. We split this group into two age bands that contained the bottom and top two age bands from the MABC (6-8, n=16; mean BPVS normalised score 101.31, SD=14.97; mean age equivalence 7.75 and 9-13, n=11; mean BPVS normalised score 114.72, SD=22.99; mean age equivalence 12.23).

The second group consisted of 20 children with autism (17 male) aged between 9 and 14 years (mean 11.9 years; mean BPVS normalised score 95.78, SD=14.15; mean age equivalence 10.76). The children were recruited through the Department of Child and Family Mental Health of the RACH, having been diagnosed using the Autism Diagnostic Interview – Revised (ADI-R; Lord *et al*, 1994), the Autism Diagnostic Observation Schedule (ADOS; Lord *et al*, 2000) and clinical observation (all patients were known clinically to one of the authors, JHGW). None had any diagnosed learning difficulties. Most (15/20) of the children were right-handed.

The third group consisted of 70 typically developing children from Scottish primary schools (35 male, 35 female). We split these children into 2 groups. The first consisted of 26 children aged 5-8 years. The second group consisted of 44 children aged 9-14 years. The typically developing children had no history of neurological or ophthalmological deficit and were reported to be performing satisfactorily within their mainstream education setting. Most (61/70) of the children were right handed.

The fourth group consisted of 40 normal adults (16 male) aged between 19 and 32 years (mean 21.5 yrs) split into two groups (half reached with their preferred hand, half with their non-preferred hand). Most (36) were right handed.

Both clinical groups had normal verbal IQ as assessed with the British Picture Vocabulary Scale (BPVS). All adult participants provided their informed consent prior to their inclusion in the study and parental consent was obtained for all of the children. The study was approved by a University ethics committee and NHS Grampian Local Research Ethics Committee.

Procedure

Stimuli were presented on a 14.1” computer screen (Toshiba Tecra M4 tablet laptop) with its screen rotated 180º from the keyboard so that the screen was upright and facing the participants. A Perspex sheet held within a wooden frame was placed in front of the screen. A small axle (0.5 cm diameter, 4 cm length) protruded from the Perspex sheet. A piece of wooden dowelling (length 5 cm, diameter 2 cm) was mounted on the axle at the centre of the long axis of the dowelling. This meant that the dowelling could freely rotate 360° in the frontoparallel plane. One end of the dowelling was coloured red, differentiating it clearly from the other end. The participants were asked to always grasp the object so that their thumb was located at the red end. A red sticker was placed on the participant’s thumbnail as an aide memoire. The participants started each trial with the tip of their index finger and thumb pinching a small moulded grip. They were seated so that the dowelling was lined up with their body’s midline. The screen was black at the beginning of each trial before the stimulus appeared in the form of a white arrow. This indicated the direction the dowelling needed to be rotated, until the red (thumb) end was aligned with a red dot indicating the end position (see Figure 1).

The participants’ task was to reach and grasp the dowelling with a pincer grip following the appearance of the white arrow, and then rotate it to an indicated final location. The dowelling started with the thumb (red) end in one of two different positions separated by 90°. This end was to be rotated 180° either clockwise or anti-clockwise, with the thumb following the white arrow (thus there were four possible trial configurations). In each position, prior to grasping, the reaching action to align the thumb with the red end could be achieved by either supination or pronation of the wrist (pronation describes the palm turning to face downwards and supination describes the palm of the hand turning to face upwards). The dowelling was positioned such that this required either 135° supination or 225° pronation of the wrist (from the starting orientation with the thumb at 9 o’clock) in half the trials, or 135° pronation or 225° supination in the other half. Anatomical constraints meant that rotating the hand by 135° in the initial reach then resulted in an uncomfortable final hand posture in half of the trials. The set-up was adjusted for left-handed people by mirror reversing the apparatus. There were eight trials per condition, making 32 trials in total.

The four conditions were presented in one of three fixed random sequences assigned randomly to participants. At the beginning of the session, participants were told “There are always two ways in which you can grasp the object” and were asked to think about which of the two ways they were going to use to remind participants that there was more than one way to perform the reach. On each trial, participants reached out and grasped the object as fast as possible, then turned it. They were asked to hold their final posture until the stimulus disappeared. The participants did eight practice trials where the experimenter ensured that the participants had followed the instructions (grasp the object with the thumb at the red end of the dowelling and turn it following the white arrow). The practice trials were followed by a three minute rest where the participants were distracted by questions regarding their daily lives, then the experiment was run. The experimenter coded each reach as pronation or supination as it happened.

RESULTS

Data analysis

From a standardised starting hand posture we asked participants to grasp a dowelling with a pincer grip and then rotate it by 180^o in either a clockwise or anticlockwise direction (equally distributed). If there were no biases affecting grip selection then the participants should randomly select a grasp (pronation or supination) on each individual trial and there should be no discernable pattern across the trials. If participants were using pronation and supination more systematically, then we might expect participants to select the minimum rotation (MR) grip (smaller rotation is faster and easier), pronating on half the trials and supinating on the other half. However, on half of all trials, selecting a minimal rotation grip would entail an awkward final position after the rotation. On these trials, participants might select the longer rotation grip in order to produce a comfortable final posture (the end-state-comfort effect, ESC). There were two additional variations – it was possible that we might see ESC dominate for one dowelling position and MR dominate at the other and second that there may be some hysteresis (repeating an initially performed action independently of these other biases. In this case, a younger child might consistently pronate or supinate their hand irrespective of condition).

In order to analyse grip selection, we looked at the four conditions (depicted in Figure 1) separately and listed the grip selected for each of the eight trials. In the majority of cases, the same grip was selected throughout the condition. Thus, we could label the response to each condition as being either pronation or supination. Consequently, there were 16 possible response patterns but we anticipated seeing only six of these:

1. If participants show repetition then all four conditions (a, b, c, and d in Figure 1) should show either (1) a consistent pronation response or (2) a consistent supination response depending on the initial reach.
2. If participants show an ‘end-state comfort’ effect then they should (3) supinate their hand when reaching to grasp the dowelling in Position 1 and turn it anticlockwise (Figure 1a) but pronate their hand when rotating the dowelling clockwise from this position (Figure 1b) with the opposite effect occurring when the dowelling is in Position 2 (Figure 1c and d;).
3. If participants show a minimal pre-contact rotation effect then they should (4) supinate their hand when reaching to grasp the dowelling in Position 1 (Figure

1a and b) and pronate their hand to Position 2 (Figure 1c and d) regardless of the direction of the subsequent turn.

4. It was also possible that we might observe (5) a minimal rotation effect at Position 1 (Figure 1a and b) but an end-state effect at Position 2 (Figure 1c and d) or (6) vice versa.

In order to explore grip selection, we simply determined the category of response pattern for each individual and then determined the frequency with which each response pattern was found within the populations under investigation.

Grip selection

For the majority of participants (103/117 children and all the adults) the grasp they selected on the first trial of a given condition was repeated on all other trials of that condition. In 14 children (10 typically developing and 4 with DCD) we observed a (single) shift from one pattern to another in the middle of the experiment. In order to analyse the data across all participants we considered the initial pattern shown by these 14 children (as being more representative of their underlying initial competence) together with the stereotypical (consistent) pattern shown across all trials by the other children.

Figure 2 shows the relative frequency with which the different groups selected the different grasp patterns. We found that all of the adults who grasped with their preferred hand showed the ESC effect across all of the trials. These results replicate those of Rosenbaum, Vaughan, Jorgensen, Barnes, and Stewart (1993). Interestingly, we found that when adults grasped with their non-preferred hand, 20% showed a MR bias. The difference between the two adult groups (preferred vs. non-preferred hand) was statistically reliable (Fisher's exact test; $p<0.05$).

It can be seen immediately that the children (who all grasped with their preferred hand) showed a different pattern when compared to the adults who used their preferred hand. A small number (5/26, 19.2%) of the youngest typically developing children showed the ESC bias across both target positions but 50% of the children showed the ESC bias for at least one of the positions (8/26, 30.8% of children showed the ESC bias at one position and the MR bias at the other position). Seven (26.9%) of the youngest children were biased to select an MR grip at both target locations.

In contrast, 81.8% (36/44) of the older typically developing children showed an ESC bias for at least one of the positions (34.1% of these children showed the ESC bias at one position and the MR bias at the other position). Only 6.8 % of the older typically developing children showed the MR at both target locations. We used Fisher's exact test to test whether the developmental trend away from MR and towards ESC bias was statistically reliable, which it was ($p<0.05$).

Figure 2 shows that both the younger and older children with DCD were biased to select an MR grip to grasp the dowelling even though this resulted in a more awkward second action. Fisher's exact test confirmed that the difference in grip selection between younger children with DCD and younger typically developing children was statistically reliable ($p<0.05$), and the same difference occurred when older children with DCD were compared to the older typically developing group ($p<0.05$). The difference in grip selection bias (MR against ESC) across the younger and older children with DCD was not statistically different between these groups (*p*=0.61).

Figure 2 also shows that some children within all those groups had a tendency towards perseveration/repetition (i.e. they generated a pronation or supination movement in all four conditions). There is a clear tendency for this behaviour to disappear with increasing age and none of our adult participants showed such a response. The repetition effect appeared to be present in children with and without DCD though. Figure 2 also shows the data from the children with autism, which was completely indistinguishable from the typically developing data. Thus, children with autism show the same pattern of grip selection as typically developing children and differed from the DCD population in this respect.

DISCUSSION

Our study explored motor planning in adults and children with and without neurodevelopmental disorder. We selected a design that allowed us to explore the relative effect of two different biases on grip selection: end-state comfort (ESC) and minimal pre-contact rotation (MR). We were also able to explore whether there was any tendency to perseverate in a selected action. We replicated previous research showing that adults are biased towards selecting a grip that results in a comfortable end-state posture after a subsequent secondary movement when using their preferred hand (Rosenbaum, et al, 1990, 1992, 1993, 1996). We found that adults who used their non-preferred hand showed a different pattern of grip selection, supporting the hypothesis that a lower prehension skill level would influence behaviour away from

ESC. We hypothesised that children might therefore be biased towards selecting a grip that decreased the difficulty of the initial movement, given that children have a lower skill level in reach-to-grasp behaviour than adults (Kuhtz-Buschbeck *et al*., 1998, Mon-Williams *et al*., 2005, Tresilian *et al*., 2005). We found a clear developmental trend in line with this hypothesis where younger children (aged 5-8 years) showed a greater bias towards selecting an MR grip than older children (aged 9-14 years). We had also hypothesised that a group of children with DCD would be biased towards MR at all ages due to their known prehension difficulties (Smyth, Anderson & Churchill 2001; Mon-Williams *et al*., 2005). The children with DCD showed the predicted bias towards MR, and the proportion of children with DCD who showed the MR bias was higher than even the youngest group of typically developing children. Moreover, there was no statistical evidence of a decrease in the proportion of older children with DCD showing this bias. Finally, we investigated whether children with autism would also show different grip selection biases, predicting that their known executive planning deficits may not translate into a motor planning deficit. In line with this, the children with autism performed identically to age-matched controls.

Our finding that children with DCD show a different grip selection bias is at odds with the study by Smyth and Mason (1997) who found no differences between their groups. Our results also appear at variance with the study by Hughes (1996) who found that children with autism were different from controls. Nevertheless, the differences can be readily explained in terms of the experimental designs. The difficulty with the designs used by Smyth and Mason (1997) and Hughes (1996) is that potential biases that affect grip selection were not well controlled and were not documented. For example, Smyth and Mason used eight different target positions and allowed children to turn the handle either clockwise or anti-clockwise from uncontrolled hand starting locations. In the present study, the task was simplified and the potential motor planning biases were carefully controlled (and documented), which allowed us to identify different subtle grip selection biases across the groups.

Differences in grip selection between adults and children have been interpreted elsewhere as indicating a deficit in planning (see e.g. Smyth & Mason 1997; Hughes 1996). The problem with such an interpretation is that a clear distinction between *motor* and *executive* planning has not been drawn. The fact that young children are biased towards selecting a grip that minimises the initial difficulties cannot be taken as evidence that they have a deficit in 'thinking ahead' (somewhat implicit within the generic descriptor of 'planning deficit'). Indeed, all of the children with DCD possessed normal IQ and showed no evidence of cognitive problems, and another sample performed within the normal range on the Tower of London test of executive function. In contrast, there is compelling evidence that children with autism have executive planning deficits (e.g. Hughes et al, 1994). Nevertheless, there was no evidence of different grip selection in the autistic population. While it is clear that these planning tasks (gripping, Tower of Hanoi, etc) all entail both executive and motor elements, these dissociations strongly suggest that the tasks *primarily* tap different processes, and that this distinction is therefore of great pragmatic value.

These findings appear to support the notion that 'executive' and 'motor' planning are two distinct mechanisms (as we suggested on theoretical grounds in the introduction). Thus, monkeys show the end state comfort effect despite a lack of executive planning skills (Weiss, Wark & Rosenbaum 2007). The executive planning deficits associated with autism may only become evident when tasks become more complex or contain competing attentional demands (i.e. tap more executive processes). Likewise, the motor planning problems of children with DCD may only be evident on tasks that isolate subtle differences in grip selection. It follows that grip selection experiments are best considered as tests of motor planning: studies of the biases that affect the selection of one action over other possibilities.

Conceptually separating motor from executive planning leads us to speculate about the underlying mechanism of the former, given what we understand about motor development. Any simple learning model predicts the selection of one action rather than another if (1) one particular action is reinforced by a positive outcome and (2) action selection is competitive. Most (if not all) motor theorists agree that such learning mechanisms underpin the acquisition of motor skills. In short, the acquisition of motor skills occurs through an evolutionary process, where a neonate's spontaneous movements are reinforced when useful ('fit') but become extinct if a more useful ('fitter') movement pattern enters the ecological action niche. The waiter who grasps the upside down wine glass with their hand uncomfortably positioned before rotating the glass into a comfortable position (in Rosenbaum's classic example) gives the appearance of someone who has explicitly weighed up the costs and benefits of their future actions. This apparent explicitly predictive behaviour might actually reflect the fact that such grasping actions have been successful in the past and are therefore selected again (though executive planning might have been the original driver that caused the initial behaviour). We suggest that motor planning works as a blind watchmaker, with actions reflecting a previous history of motor evolution where useful actions have survived and less useful ones have perished. This then accords nicely with the current data. Children with DCD seem to be taking their movement difficulties ‘into account’ by selecting the simpler movement, but by our account are actually reproducing movements that past experience has shown to be successful. In the same way, younger typically developing children use less efficient movements because those are the most reliable movements they have yet produced, and hence the ones favoured during learning. Older children have experienced and reinforced the more efficient action (driven to transition by the costs that arise from using an inefficient action) while adults have great experience with an efficient reach using their preferred hand, but less experience in their non-preferred hand. No one ‘failed to plan’ – instead, they reached in accordance with their experience and ability (their developmental motor status). We note in conclusion that in this account ‘executive’ planning allows us to escape the shackle of reliance on previous experience, and *action planning* is the subtle interplay between learned behaviour and postulated abstract outcomes.

In summary, our results show a developmental pattern in grip selection. Moreover, our findings indicate that children with movement problems (DCD) are biased towards selecting grips that minimise the initial difficulty of a two-stage movement. We have interpreted our results in terms of the developmental motor status of the individual and the factors that bias action selection. Our results suggest that previous studies have conflated two different types of 'planning' (motor and executive) and that the observed differences found between children with and without DCD, adults and children with autism reflect varying strengths and weaknesses in tasks that primarily involve one, the other or both of these components.

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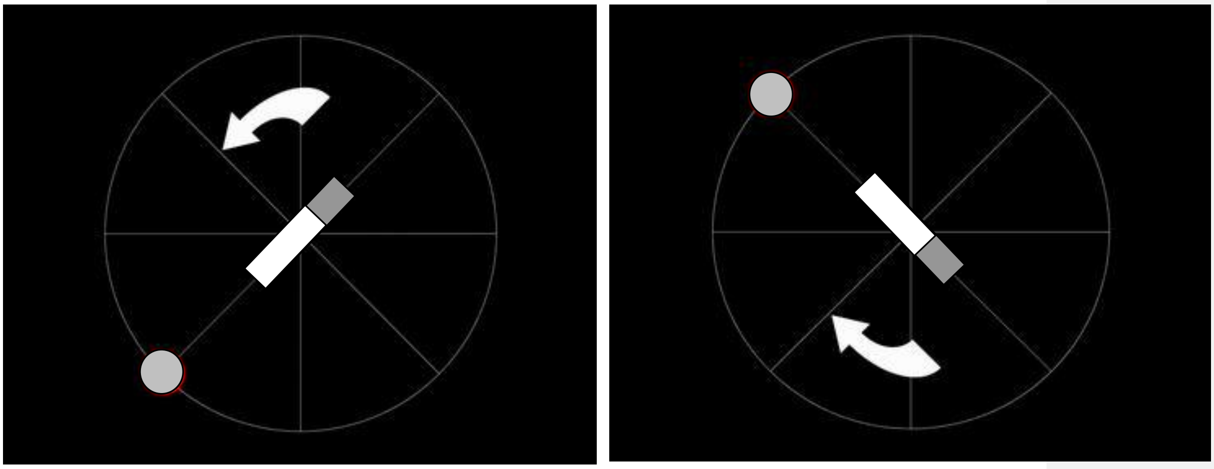
FIGURE CAPTIONS

Figure 1. The four different configurations for right-handed participants (reversed for left-handed participants). The pieces in grey (the dot and one end of the dowelling) were red in the experiment. Participants began each trial with their hand pinching a moulded grip so that their thumb began at 9 o’clock – degrees of rotation are measured with respect to this.

The top pictures show the dowelling/arrow combinations in which reaching to grasp the dowelling according to the minimal rotation bias still allowed end state comfort after turning the dowelling. The bottom two pictures show the combinations in which these two biases were placed in opposition – selecting the initial reach on the basis of minimal rotation then entailed a uncomfortable end state after turning the dowelling.

Figure 2. The relative frequency with which the different grasp patterns were selected by the different groups.

Initial Minimal Rotation Allows End State Comfort



Initial Minimal Rotation Prevents End StateComfort

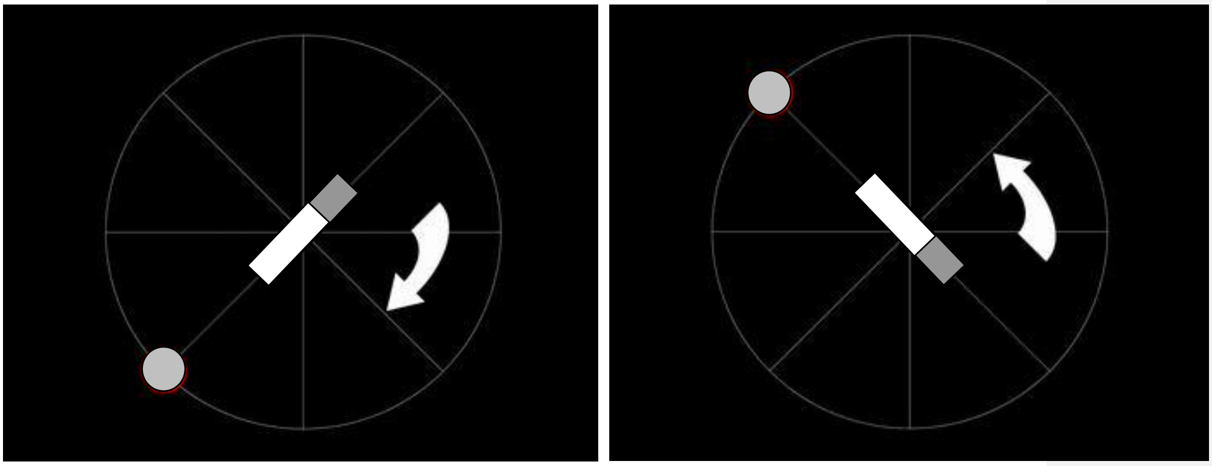


Figure 1.

Motor planning

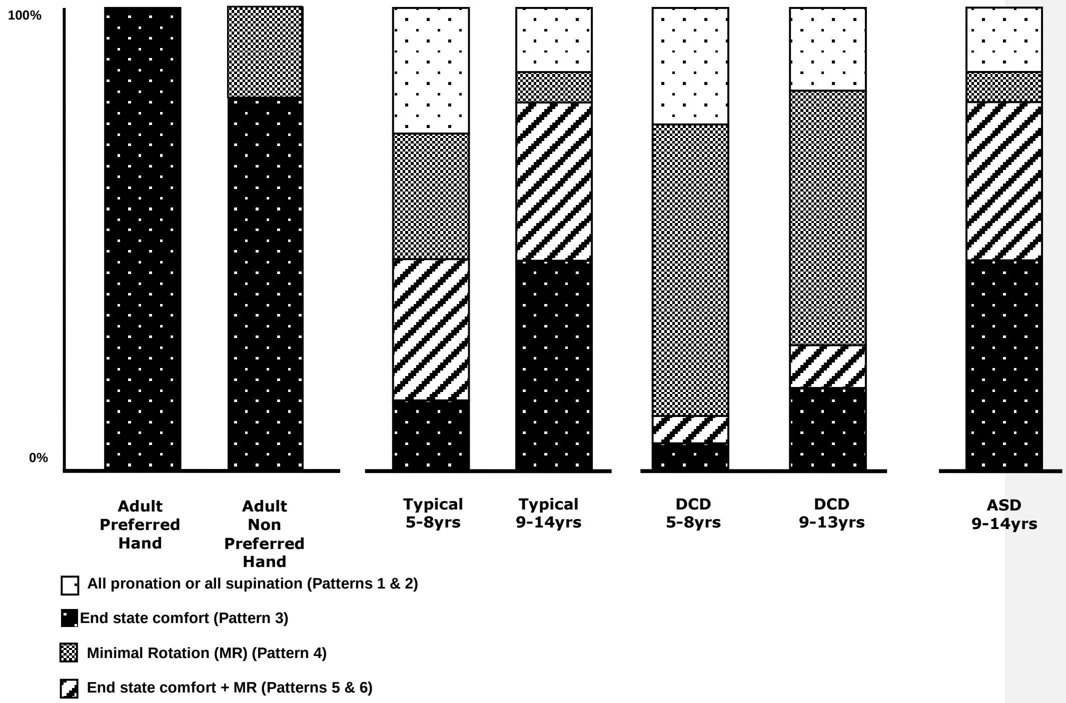


Figure 2.