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A Sensorimotor Approach to the Training of Manual Actions in Children With Developmental Coordination Disorder

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Abstract

Developmental coordination disorder affects a relatively large proportion (5%-6%) of the childhood population. Severity of the disorder varies but there is a great need for therapeutic intervention. We propose a method for the training of manual actions in children with developmental coordination disorder. Our solution is achieved by applying haptic virtual reality technology to attack the difficulties that children with developmental coordination disorder evidence. Our results show that children with developmental coordination disorder are able to learn complex motor skills if proper training methods are employed. These findings conflict with reports of impaired motor learning in developmental coordination disorder because of underactivation of cerebellar and parietal networks.

Keywords

developmental coordination disorder, sensorimotor training, manual actions, virtual reality

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Developmental coordination disorder is understood to be, first and foremost, a motor disorder[1-9] although it is often comorbid with Autism Spectrum Disorder and Attention Deficit Hyperactive Disorders, among other general perceptual and cognitive disorders.[10] Children with developmental coordination disorder can exhibit poor gross motor control, poor fine motor control, or both.[3] Moreover, this motor disorder can lead to emotional and academic problems.[10-12] For instance, children with developmental coordination disorder commonly have problems with spelling and reading[13] in addition to difficulties with tasks like writing.

Developmental coordination disorder is also thought to be a learning disability as children with developmental coordination disorder often have persistent trouble learning or acquiring motor skills.[6,14-17] Given the difficulties that children with developmental coordination disorder have learning or acquiring motor skills and given the cerebellum's known role in motor learning processes, it has been hypothesized that cerebellar dysfunction is a possible source of motor disruptions observed in individuals with developmental coordination disorder[18-20] and there is some evidence supporting these claims. Specifically, Zwicker and collaborators[17] found that children with developmental coordination disorder demonstrated underactivation in cerebellar-parietal and cerebellar-prefrontal networks. However, there is also some evidence suggesting that dysfunction of the parietal brain regions (left posterior parietal cortex and left postcentral gyrus) may underpin impaired motor skill performance in children with developmental coordination disorder.[21] It is not clear whether neural differences are the cause or a correlation, raising the question of whether children with developmental coordination disorder are able to exhibit effective perceptuomotor learning. In the present study, we find that they can learn effectively with appropriate support.

Researchers have investigated a number of possible etiologies of developmental coordination disorder including deficits in attention[22,23] or in kinesthesia.[24-26] There has also been the suggestion that children with developmental coordination disorder are reliant on visual information and show kinesthetic deficits.[26-28] It has been further suggested that the root of the

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problem for children with developmental coordination disorder lies in deficits in the mappings from sensory to motor systems.[4-6,8,9] This notion is consistent with deficits in both parietal and cerebellar areas of the brain.[22,25] The result is poor performance in a variety of sensorimotor tasks such as targeted reaching, manual manipulation, and coordination tasks.[6,8,9,29-31]

Research on the control and coordination of limb movements has shown that the sensorimotor control of limb stiffness and compliance is a key element in the organization of motor systems.[32-40] Logically, the best training for children with developmental coordination disorder would focus on the sensorimotor organization intrinsic to the control and coordination of the limbs, that is, limb stiffness and compliance. The therapeutic goal must be to allow the children to improve the perceptual abilities intrinsic to the concurrent generation and experience of their own movements and the use of that information to guide their movements.

This sort of training ("sensorimotor training") is difficult to implement with traditional therapeutic tools and methods. However, robot-assisted therapies such as those involving the MIT-MANUS,[41,42] the Assisted Rehabilitation and Measurement Guide,[43] and the Mirror-Image Motion Enabler[44,45] are being developed and should assist in the development of new therapeutic tools. One of the motivations behind the development of such robotic systems is the relative disparity between the number of therapists and the number of patients, coupled with the amount of "therapy time" required for functional improvements. Robot-assisted therapies allow for training to occur independently of a therapist, that is, without the direct supervision of a trained therapist. In addition, robots can apply various constraints to the required movement patterns and, thus, the complexity and/or difficulty of a motor task can be controlled very precisely.[46] Ben-Pazi and collaborators,[47] for example, showed how robots could be used with children to improve the generation of handwriting movements. In this experiment, Ben-Pazi et al determined that the mechanical properties (inertia and viscosity) of a robot pen (Phantom 1.5) affected handwriting quality of 8- to 14-year-old children. Specifically, Ben-Pazi et al found that increased inertia and viscosity of the pen reduced high-frequency components in handwriting movements and improved handwriting quality. The improvements in handwriting legibility were found for both teacher ratings and layperson ratings of handwriting quality.

The results from Ben-Pazi et al[47] are very promising regarding the utility of robot-assisted therapies for children. However, the nature of the support provided by the robot needs to be examined. For example, Bingham and collaborators (personal communication) found that passive training of the sort provided by some of these robot-assisted therapies failed to enable good sensorimotor learning of new movement tasks (ie, the training failed to transfer beyond the very specific movements that were practiced). Instead, active sensorimotor generation and control of movement trajectories was required for learning that generalized to task-related movements other than those specifically practiced. This result suggests that children with developmental coordination disorder face a difficult "catch-22" situation.

Motor learning was described by Newell[48] as having 2 stages. First, the learner acquires a qualitative approximation to the movements to be learned. Once this is achieved, the learner can quantitatively improve the performance through practice. The apparent problem for children with developmental coordination disorder is they cannot achieve a sufficiently good qualitative approximation to be able to then make good quantitative improvements through practice. This is the catch-22. Robot-assisted therapies could, in principle, help them achieve the essential movement form, but it is likely that this must be done under active sensorimotor control to be effective. Many of the existing robot-assisted therapies do not allow such active control. The problem is to find a way to support and guide the movements while requiring them to be actively generated and controlled. The best method of support would allow children with developmental coordination disorder to perform with support as well as age-matched typically developing children. This would keep the motivation and, potentially, self-esteem of the learners high. If the approach to learning is effective, then the level of support can be gradually (ie, parametrically) reduced while maintaining the high level of performance until finally the learners are able to perform without support as well as typically developing children.

So the initial question is how to support performance of movements while requiring that they be actively generated and controlled?

Initial Study: Finding Appropriate Control Variables

Much of the research on children with developmental coordination disorder focuses on identifying differences between children with developmental coordination disorder and typically developing children: children with developmental coordination disorder are typically found to be slower and less accurate on most tasks when compared to their typically developing peers. De Oliveira and Wann[49] indicated that these differences were important for diagnostic purposes but suggested that it is essential to find conditions where children with developmental coordination disorder are relatively unimpaired to better understand the underlying causes of developmental coordination disorder. The purpose of this study was to test robot-generated properties to identify a parametric variable that would allow children with developmental coordination disorder to perform similarly to typically developing children or even adults when interacting with a robotic haptic device. Ben-Pazi et al[47] showed that viscosity and inertial properties may provide appropriate support, but these do not allow provision of a template for the movement form. Furthermore, there was no evidence that the method did or even could generalize to performance without the support provided by the method. We adopted an alternative approach. We provided a movement template as a wire path that was to be followed or traced by the tip of a stylus held, like a pencil or pen, by the child. This is difficult for any performer,

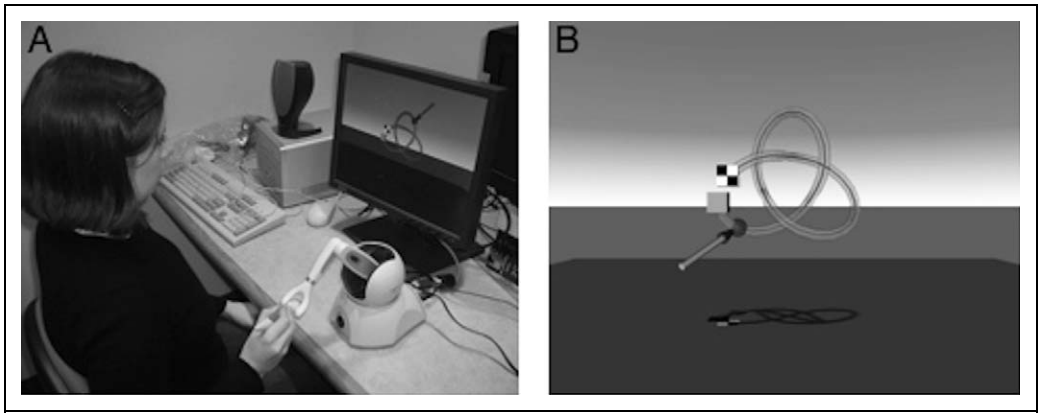

Figure 1. (A) Example of display and target path. (B) The Phantom together with the display.

but it is nearly impossible for a child with developmental coordination disorder, because that child inevitably comes off the path and has to regain it over and over again. How might such a child be supported to avoid the extreme frustration this would provoke? The method would need to be open to parametric variation. The potential solution that we investigated was to make the wire path ''magnetically attractive'' to the stylus tip. With strong attractive force, the child can concentrate on moving the stylus along the 3-dimensional path in space. The most compliant motions become the most successful and this is exactly what a child with developmental coordination disorder needs to learn. (A common observation is that these children press their pencil or pen into a writing surface to try to gain some measure of control through highly noncompliant movement.) The question is whether this parameter allows children with developmental coordination disorder to perform as well as age-matched typically developing children. Here, we test the effect of both ''magnetic attraction'' and ''friction'' along the path.

Method

Participants. Three boys with developmental coordination disorder aged 12 years 2 months, 9 years 9 months, and 12 years 4 months were tested along with 2 age-matched typically developing boys (12 years 9 months, and 10 years 4 months) and 3 normal adults, aged 27, 30, and 53. The children with developmental coordination disorder were recruited at a local children's physical and occupational therapy clinic and were identified as having motor problems that significantly interfered with their activities at school and at home. One of these children had a Bruininks-Oseretsky upper-limb speed and dexterity *z*-score of –1.66 and a bilateral coordination *z*-score of –1.46 (both of which indicate ''poor performance''). Another child had Beery-Buktenica Developmental Test of Visual-Motor Integration scores of 0.8th percentile (visual perception skills), 19th percentile (motor coordination skills), and 23rd percentile (overall visual motor integration skills). The third child had Beery-Buktenica Developmental Test of Visual-Motor Integration scores of 19th percentile (visual perception skills) and 13th percentile (overall visual motor integration skills). The typically developing children were not formally evaluated but had normal vision and no history of motor or neurologic impairments. This study was approved by the Indiana University Institutional Review Board; the children participated with informed assent with consent from their parents/guardians.

Procedure. All participants performed the same basic 3-dimensional tracing task. The task was to use a virtual stylus (controlled in a similar manner to a computer mouse) to push a bead along a 3-dimensional path visible in a computer graphic display (see Figure 1) from a starting location (the plain square) to a finishing point (the checkered square). The participant grasped a stylus that was attached to a desktop force feedback haptic virtual reality device, a Phantom Omni from Sensable Technologies, and used the stylus to control the virtual stylus to feel the path and push the bead. The path attracted the stylus to hold it on the path (as if a magnetic force were present). The ''magnetic'' strength was parametrically varied to alter task difficulty. Path ''friction'' was a second parameter. Participants performed 3 random order blocks of 9 trials (27 total trials) in which the bead was pushed around the wire path seen in Figure 1. In a block, a trial was a combination of level of friction (low, medium, or high) and level of magnetic attraction (low, medium, or high).

Data Analysis. The 3-dimensional Cartesian coordinates of the virtual stylus tip and red bead were recorded at 50 Hz. These data were filtered using a dual-pass, second-order Butterworth filter with a 5 Hz cut-off frequency. Using these data with the known coordinates of the target trajectory (the wire), the trial duration and path length were computed to evaluate performance. Path length was then normalized so that ideal performance was equal to 1. We averaged trial duration and normalized path length, for each participant, over the trials performed in a given condition.

Results

Trial durations for all participants under all conditions are reported in Figure 2A whereas path length is reported in Figure 2B. Overall, adult performance was best, followed by that of typically developing children and then children with developmental coordination disorder. Importantly, the performance of children with developmental coordination disorder was comparable to that of typically developing children when the magnetic attraction was strong and the friction was low. Performance was strongly affected by magnetic attraction. When magnetic attraction was low, everyone tended to come off the wire and had to spend time getting back onto it, but

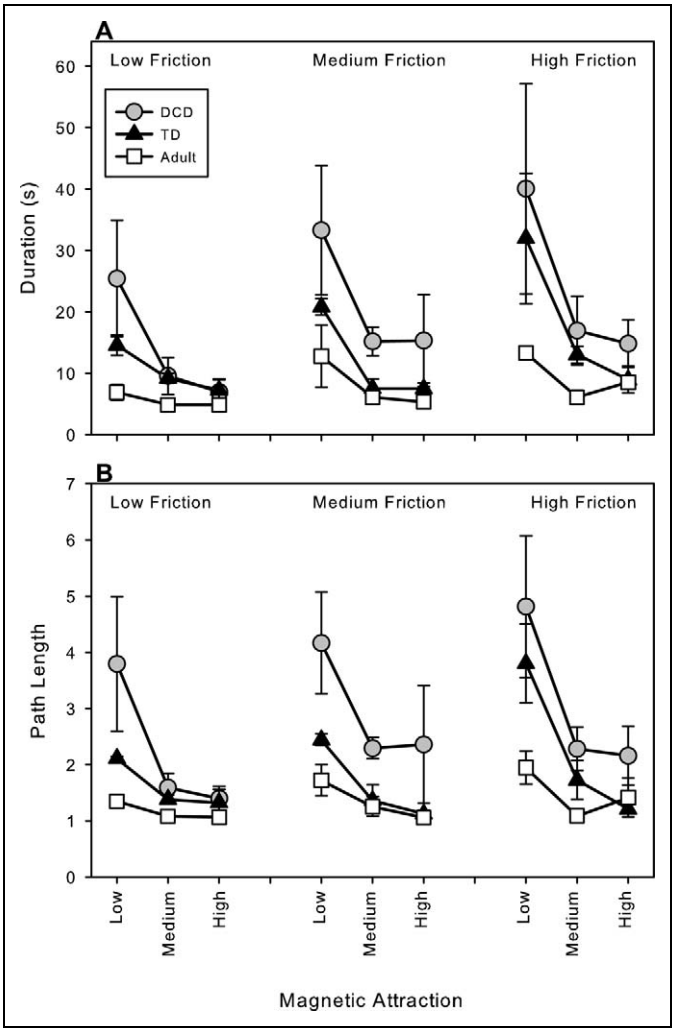

Figure 2. (A) Trial durations and (B) normalized path length for each condition (friction level and level of magnetic attraction) by groups of participants: adults (white squares); typically developing (TD) children (filled triangles); children with developmental coordination disorder (DCD, filled circles).

children with developmental coordination disorder did this more often than did typically developing children and adults. The differences in performance were obvious at the time of testing. The task was successful in 2 respects: it differentiated children with developmental coordination disorder from typically developing children and at the same time allow children with developmental coordination disorder to perform like typically developing children with appropriate variation in the magnetic parameter, yielding those children good efficacy. Again, adjustment of the task parameters could make the child with developmental coordination disorder appear normal in terms of his or her comparative level of performance.

Main Study: Do Children With Developmental Coordination Disorder Improve?

The purpose of this experiment was to determine whether the quality of movements generated by children with developmental coordination disorder can be improved with progressively less support from the robot. Given the results from the first study, we elected to remove friction as a parameter and only to vary level of magnetic attraction.

Participants

Eight 7- and 8-year-old children with developmental coordination disorder participated in this study; 4 were recruited from a local physical and occupational therapy clinic and 4 were recruited from a local elementary school. The children recruited from the local clinic were evaluated (given a standardized test of the clinician's choice) by a trained therapist and referred to us for enrollment. These children all scored lower than the 10th percentile on a relevant standardized test (Beery-Buktenica Developmental Test of Visual-Motor Integration, Developmental Test of Visual Perception–2: eye-hand coordination subtest, Wide Range Assessment of Visual Motor Abilities: pegboard/fine motor subtest). The children recruited from the local elementary school were evaluated by a trained clinical psychology student using the Beery-Buktenica Developmental Test of Visual-Motor Integration; the parents/guardians also evaluated their child using the Developmental Coordination Disorder Questionnaire[50] (DCD-Q '07). These children scored lower than the 10th percentile on the overall visual motor integration test or the coordination subtest of the Beery-Buktenica Developmental Test of Visual-Motor Integration and were identified by their parents/guardians as having "suspected developmental coordination disorder" were considered to have developmental coordination disorder. The average coordination subtest score for these children was 4.0%.

Eight 7- and 8-year-old typically developing children were recruited from a local elementary school. Twenty-eight children, 7 children from 4 different classrooms, were initially screened using the Beery-Buktenica Developmental Test of Visual-Motor Integration and the Developmental Coordination Disorder Questionnaire. To be included in the analyses, the typically developing children had to closely match the children with developmental coordination disorder with respect to age, gender, and handedness, had to be free from any known medical or neurologic conditions, and were not suspected of having developmental coordination disorder as indicated by the Developmental Coordination Disorder Questionnaire and also scored >16% on the coordination subtest of the Beery-Buktenica Developmental Test of Visual-Motor Integration. The average coordination subtest score for these children was 34.6%. A t test demonstrated that coordination scores for typically developing children were significantly higher than those of children with developmental coordination disorder ($t = –4.3714$, $P < .01$).

This study was approved by the Indiana University Institutional Review Board; the children participated with informed assent with consent from their parents/guardians.

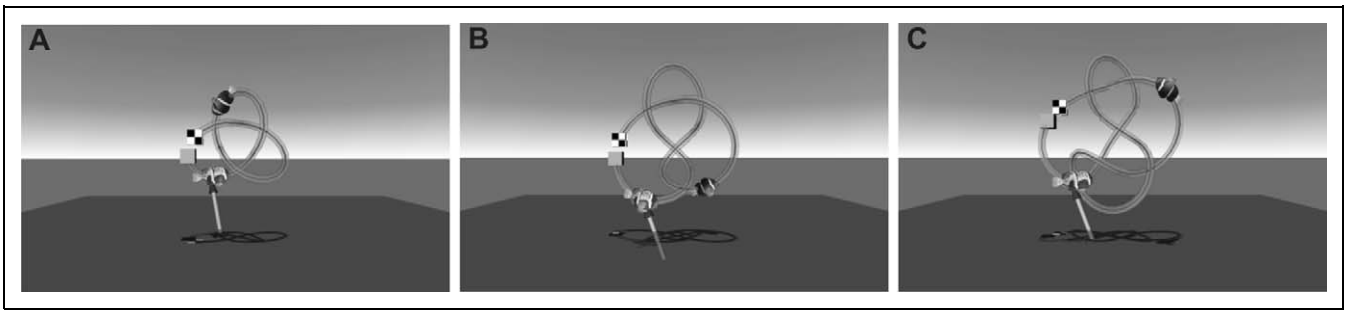

Figure 3. (A) Shortest path. (B) Middle length path. (C) Longest path.

Procedure

All participants performed the same basic 3-dimensional tracing task before and after training. The task was to push a brightly colored fish along a visible path on a computer screen from the starting location (the plain square) to the finish point (the checkered square) while racing a competitor fish. The purpose of the competitor fish was to give the children a clear temporal goal. As in Experiment 1, the participants grasped a stylus that was attached to a desktop force feedback haptic virtual reality device, a Phantom Omni from Sensable Technologies, and used the stylus to feel the path and push the fish. The path magnetically attracted the stylus to hold it on the path. The magnetic strength was parametrically varied to alter task difficulty. Participants attempted 2 trials at each of 8 levels of magnetic attraction on the path pictured in Figure 1B while racing a competitor fish that took 20 seconds to travel the path from start to finish. From pilot testing, it was clear that most children would spend many minutes to complete a path and would become very frustrated with the lack of progress so each trial was terminated if a child could not complete more than one-half of the path within 60 seconds.

All participants were then given up to five 20-minute training sessions that were separated by 1 week (sometimes 2 in the case of illness). During the training, there were 3 different paths that varied in length, curvature, and torsion (see Figure 3). There were also 2 different competitors against whom the participants were racing: one that completed the path in 30 seconds and another that completed the path in 10 seconds. On a few occasions, we used a third competitor whose speed was in between the other competitors (20 seconds) but this was only if a participant was struggling with the fastest competitor.

The training started with the highest level of magnetic attraction, slowest competitor, and shortest path. The goal of the training was to allow the children to progress at their own pace through the different combinations of levels of attraction, paths, and competitors so we used a "2 wins in a row" rule in order to determine when the children progressed. (On a few occasions, we allowed a participant to progress without "winning" 2 times in a row; these instances happened only after a participant tried the type of trial a few times and expressed a great deal of frustration about not winning.) After the participant "beat" the slowest competitor 2 times in a row, he or she progressed to the faster competitor. Once the participant beat both competitors he or she then moved to the next longest path (with slowest competitor). After all paths and competitors were "beaten," the level of magnetic attraction was decreased and the participant restarted with the shortest path and slowest competitor.

Data Analysis

The 3-dimensional Cartesian coordinates of the virtual stylus tip and fish were recorded at 50 Hz. These data were filtered using a dual-pass, second-order Butterworth filter with a 5 Hz cut-off frequency. Using these data with the known coordinates of the target trajectory (the wire), the trial duration and normalized path length were computed to evaluate performance. We then averaged trial duration, for each participant, over the trials performed in a given condition (path, competitor, level of magnetic attraction). For the (baseline) trials where children were unable to complete the path, a value of 60 seconds was given for the trial duration; the average path length of the last level completed was given for all subsequent levels. Average trial duration and normalized path length, before and after training, were then analyzed using 3-way mixed-design analysis of variance with the following conditions and levels: group (developmental coordination disorder, typically developing), level of magnetic attraction (1-8), and session (baseline, posttraining). Group was between subjects whereas level and session were within subjects.

Finally, we derived learning curves from the training data. The training method was designed to preserve high self-efficacy by allowing the children with developmental coordination disorder to continue to perform well with support. They started training with high levels of support and as they improved, the level of support was gradually decreased. This meant that the mean durations during training remained fairly constant and that level of support effectively represented time over the course of training. We derived learning curve data by scaling durations at each successive level of support over training by the mean duration for that level of support obtained in baseline trials before training (for the shortest path only). We then performed linear regression on the resulting data to reveal the respective rates of change for the 2 groups. Similar analysis was performed with duration and path length measures.

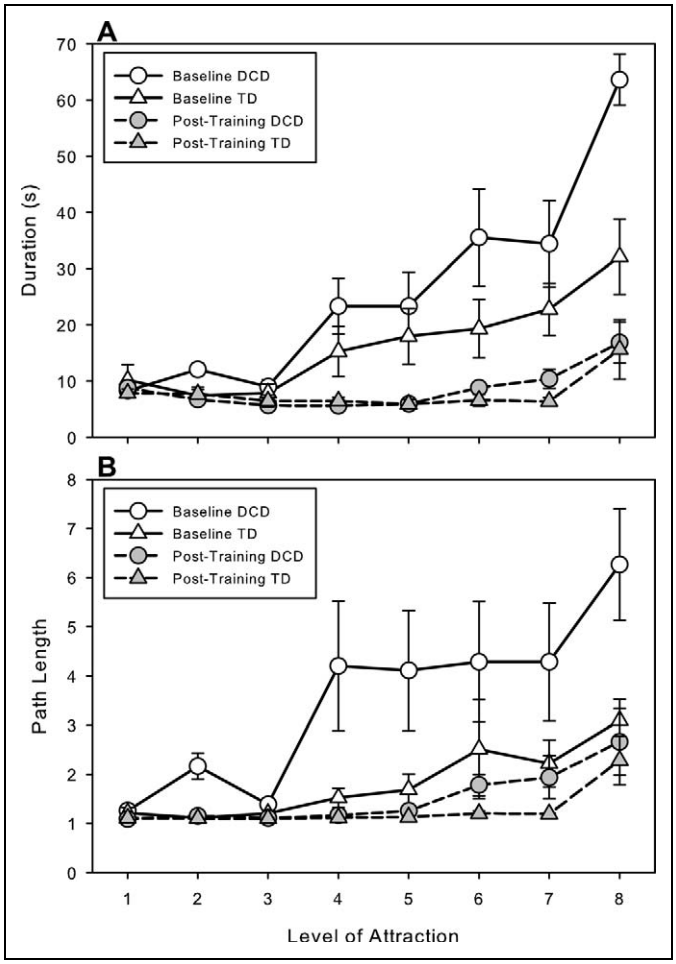

Figure 4. (A) Trial durations and (B) normalized path length across different levels of magnetic attraction for typically developing (TD) children (triangles), children with children with developmental coordination disorder (DCD, circles) before (open symbols) and after (filled symbols) training.

Results

Figure 4A shows trial duration, before and after training, for typically developing children and children with developmental coordination disorder across the different levels of magnetic attraction (1 = highest level, 8 = lowest level). Before training, performance by children with developmental coordination disorder was significantly worse than performance by typically developing children. Trial durations for children with developmental coordination disorder were much longer without support (although by design performance was comparable with high levels of support). After training, both groups improved significantly with the important result that performance levels for both groups were the same both with and without support.

The analysis of variance yielded a group by level by session interaction ($F_{(7,98)} = 3.35$, $P < .01$). There were also significant interactions of group by level ($F_{(7,98)} = 3.52$, $P < .01$), group by session ($F_{(1,14)} = 5.59$, $P < .05$), and level by session ($F_{(7,98)} = 15.75$, $P < .01$) as well as main effects of level ($F_{(7,98)} = 28.71$, $P < .01$) and session ($F_{(1,14)} = 49.54$, $P < .01$). The 3-way interaction indicates that the groups' performance across the levels of support changed differently, with respect to each other, from baseline to posttraining. Further testing revealed that there was a significant interaction of group and level ($F_{(7,98)} = 4.05$, $P < .01$) as well as a main effect of level ($F_{(7,98)} = 26.01$, $P < .01$) during baseline but not at posttest. There was only an effect of level at posttest ($F_{(7,98)} = 8.07$, $P < .01$).

Figure 4B shows normalized path length, before and after training, for typically developing children and children with developmental coordination disorder across the different levels of magnetic attraction (1 = highest level, 8 = lowest level). The pattern of results was essentially the same as for the duration measure. There were several significant 2-way interactions (group by session: $F_{(1,14)} = 5.78$, $P < .05$, and level by session: $F_{(7,98)} = 4.02$, $P < .01$) as well as main effects (group: $F_{(1,14)} = 4.81$, $P < .05$, level: $F_{(7,98)} = 11.30$, $P < .01$, and session: $F_{(1,14)} = 17.83$, $P < .01$) but no 3-way interaction. The group by week interaction indicates that the groups' performances changed differently, with respect to each other, from baseline to posttraining. Further testing revealed that there were significant main effects of group ($F_{(1,14)} = 5.34$, $P < .05$) and level ($F_{(7,98)} = 8.07$, $P < .01$) during baseline but not after training; there was only an effect of level at posttest ($F_{(7,98)} = 9.00$, $P < .01$).

These combined results show that both groups of children improved as a result of training but that children with developmental coordination disorder made more substantial improvements that enabled them to catch up with their typically developing peers.

Figure 5 shows the improvement that both typically developing children and children with developmental coordination disorder exhibited over the course of training in both duration (Figure 5a) and path length (Figure 5b), where level of magnetic attraction effectively represented time during training. For both groups and both measures, the resulting regressions indicated that improvement is related to level of magnetic attraction. Developmental coordination disorder: duration improvement = 6.51 × Level – 11.84 ($r^2 = 0.74$); path improvement = 0.50 × Level – 0.51 ($r^2 = 0.47$). Typically developing: duration improvement = 2.73 × Level – 4.00 ($r^2 = 0.64$); path improvement = 0.21 × Level – 0.58 ($r^2 = 0.28$). Using multiple regression to test these apparent differences in slopes (and intercepts) revealed that group (developmental coordination disorder vs typically developing) had a significant effect on the relationship between level and duration improvement (slope: $t = –13.77$, $P < .01$; intercept: $t = 5.01$, $P < .01$; overall: $F_{(3,568)} = 634.2$, $P < .01$, $r^2 = 0.77$), and path length improvement (slope: $t = –7.36$, $P < .01$; intercept: –0.33, $P > .05$; overall: $F_{(3,568)} = 251.7$, $P < .01$, $r^2 = 0.57$); that is, the slopes for children with developmental coordination disorder, for both measures, were higher than those for typically developing children. These results indicate that improvement was accelerated during training for children with developmental coordination disorder relative to their typically developing peers.

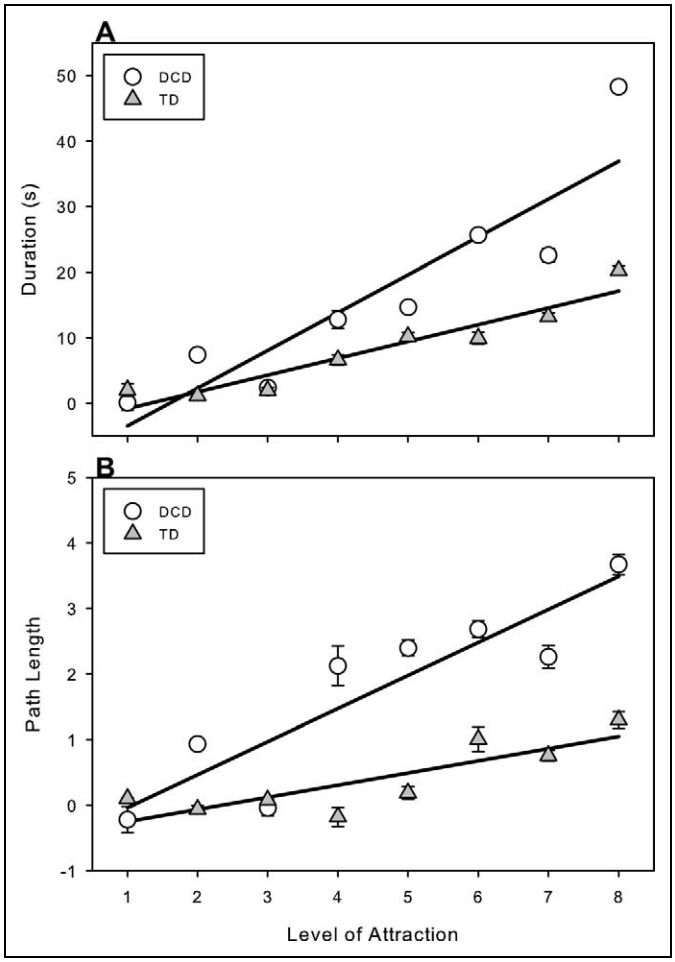

Figure 5. Improvement in (A) trial duration and (B) path length across the different levels of magnetic attraction during training for typically developing (TD) children (triangles) and children with developmental coordination disorder (DCD, circles).

Finally, we found that the children performing the task in this study clearly exhibited enjoyment of and enthusiasm for the task and expressed disappointment when we told them that the study was completed. We had made every effort to maintain high self-efficacy in the children and their evident positive response indicated that we had succeeded.

Discussion

The purpose of these experiments was to investigate the effectiveness of a novel sensorimotor paradigm for the training of manual actions performed by children with developmental coordination disorder. The children with developmental coordination disorder initially produced less successful actions, resulting in high trial durations with longer path lengths. With training, however, these children were able to catch up with their typically developing peers. These findings are particularly significant because they are among a small set of motor learning data which show that children with developmental coordination disorder are able to learn even complex motor skills when given an appropriate learning environment.

Action theory suggests that learners need to generate movements actively to be successful.[51] Children with developmental coordination disorder, however, largely cannot improve their motor performance because reliable approximations of a target action are needed to do so and these children are unable to achieve these approximations on their own. Here, we have demonstrated a method that enables children with developmental coordination disorder to overcome this catch-22 situation to be able to improve manual performance progressively to match typically developing children and to do so while performing (with implicit support) at a level comparable to that exhibited by age-matched, typically developing children. This motivated children with developmental coordination disorder to work to develop good motor skills.

Our solution was achieved by applying haptic and visual virtual reality technology developed for visualization of knots by topologists to attack the difficulties that children with developmental coordination disorder experience. The technology provided adjustable but essential support in a way that required active sensorimotor generation of movements and kept the task challenging so the children learned. The method provided support for development of good compliance control of the arm and hand in a tracing task. This meant that the children were able to produce the requisite initial ballpark movements that could be practiced to yield quantitative improvements in sensorimotor sensitivity and control. This adjustability is an important feature because although nearly all children with developmental coordination disorder have persistent trouble learning or acquiring motor skills,[6,14-17] no single neurologic condition gives rise to developmental coordination disorder. Some children with developmental coordination disorder will demonstrate underactivation in cerebellar-prefrontal networks.[17] However, others will demonstrate dysfunction of the parietal brain regions.[21] So it is likely that different remediation strategies may be required depending on the specific nature of the deficit exhibited by children with developmental coordination disorder, and we are able to achieve this flexibility through the use of virtual reality technology.

The results from this method of training allow us to revisit and re-assess the relationships between brain and behavior. A number of studies, both behavioral and imaging, have demonstrated that cerebellar dysfunction and/or parietal dysfunction are plausible sources of motor disruptions observed in children with developmental coordination disorder.[21,22,25] At present, however, there is only 1 study that has examined whether children with developmental coordination disorder recruit a different set of brain regions than typically developing children during a motor learning task. Zwicker and collaborators[17] mapped brain activity that was associated with the learning of a trail-tracing task in children with developmental coordination disorder and typically developing children. They examined the reduction in tracing error from early practice to retention and found that children with developmental coordination disorder demonstrated poorer tracing accuracy than typically

developing children at retention (when testing effect size). They also found that children with developmental coordination disorder showed less blood oxygen level–dependent signal as compared to typically developing children in cerebellar-parietal and cerebellar-prefrontal networks and in other brain regions that Zwicker et al associated with visual-spatial learning. Zwicker et al suggested that their data support a neurobiological correlation with impaired learning of motor skills in children with developmental coordination disorder; that is, underactivation of cerebellar and parietal networks is related to, and perhaps causes, poor motor learning outcomes for children with developmental coordination disorder. Our data, however, suggest that underactivation of cerebellar or parietal networks observed in children with developmental coordination disorder might reflect the absence of recruitment of a neural circuit underpinning a skill but the developmental coordination disorder population are able to recruit brain networks that support perceptuomotor learning nevertheless, and develop the requisite neural circuits for a particular skill, when they are provided appropriate support in the context of a training regime designed to maintain good self-efficacy.

In conclusion, our findings support the view that children with developmental coordination disorder perform manual actions differently than typically developing children but that they are able to learn to control the movement of their limbs when given training that includes appropriate parametrically controlled support, enabling maintenance of high self-efficacy during practice. The successful learning was particularly evident when the initial poor performance of children with developmental coordination disorder was compared to their performance after training as well as to the performance of their typically developing peers. In addition, we have identified a rate of learning that might be used to assess the progress that children with developmental coordination disorder exhibit during the course of treatment. This learning rate measure also showed good perceptuomotor learning by these children with developmental coordination disorder.

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Author Contributions

All authors made substantial contributions to the conception and design and interpretation of the data and approved the final article version. WSC drafted the article; MMW and GPB revised the article for important intellectual content.

Declaration of Conflicting Interests

The authos declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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