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TRAINING COMPLIANCE CONTROL YIELDS IMPROVED DRAWING IN 5–11 YEAR OLD CHILDREN WITH MOTOR DIFFICULTIES

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Abstract

There are a large number of children with motor difficulties including those that have difficulty producing movements qualitatively well enough to improve in perceptuo-motor learning without intervention. We have developed a training method that supports active movement generation to allow improvement in a 3D tracing task requiring good compliance control. Previously, we tested a limited age range of children and found that training improved performance on the 3D tracing task and that the training transferred to a 2D drawing test. In the present study, school children (5–11 years old) with motor difficulties were trained in the 3D tracing task and transfer to a 2D drawing task was tested. We used a cross-over design where half of the children received training on the 3D tracing task during the first training period and the other half of the children received training during the second training period. Given previous results, we predicted that younger children would initially show reduced performance relative to the older children, and that performance at all ages would improve with training. We also predicted that training would transfer to the 2D drawing task. However, the pre-training performance of both younger and older children was equally poor. Nevertheless, post-training performance on the 3D task was dramatically improved for both age groups and the training transferred to the 2D drawing task. Overall, this work contributes to a growing body of literature that demonstrates relatively preserved motor learning in children with motor difficulties and further demonstrates the importance of games in therapeutic interventions.

Keywords

Transfer of learning; Motor learning; Children; Figure copying; Cross-over design; Haptic guidance; Haptic training

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1. INTRODUCTION

Children have to learn to perform skilled movements from walking to throwing to handwriting. There are many routes that a child can take to achieve motor goals, but it seems that most children converge on a common solution set and behaviors of different children appear very similar (i.e. see Snapp-Childs & Corbetta, 2009). Nevertheless, there is a segment of the childhood population that, for one reason or another, does not follow the expected trajectory of motor development. The issue for teachers, therapists, parents and the like is how to intervene to help these children to improve their motor skills and potentially “catch-up” to their peers. A traditional approach has been to model desired movement skills for the child with the hope that the child will acquire the correct form of the required skill and then improve with subsequent practice. This approach has taken several forms. For instance, an adult expert (teacher, movement therapist) will physically move the child's limbs through the desired form of movement (called “active assist”). Likewise, robotic approaches have been developed to do the same (for reviews, see Kwakkel, Kollen & Krebs, 2008; Marchal-Crespo & Reinkensmeyer 2009). Generally, however, passive robotic approaches to therapy are ineffective (Lo, Guarino, Richards, Haselkorn, Wittenberg, et al., 2010; Reinkensmeyer & Patton, 2009; Wong, Kistemaker, Chin, Gribble, 2012) and do not lead to robust learning (for examples, see Beets, Macé, Meesen, Cuypers, Levin, et al. 2012; Goodwin, 1976; Snapp-Childs, Casserley, Mon-Williams & Bingham, 2013). However, recent efforts to develop active robotic and/or virtual reality based training systems have shown great promise to be effective tools for intervention for children with motor difficulties (for examples see Golomb et al., 2010; Meyer-Heim et al., 2009).

With the aforementioned findings in mind, we developed a method to train children to attain better manual control (Snapp-Childs, Mon-Williams & Bingham, 2013). Children are required to perform a complex 3D tracing task actively while being supported. The child holds a stylus in the hand and uses it to control a virtual stylus with which they are to push a virtual bead around a complex 3D shaped path. One of the features of this task is that keeping the stylus in contact with the path can be made easier or more difficult. The robotic arm was modeled as a virtual spring that acted on the stylus so as to hold it onto the path giving the phenomenological impression of a ‘magnetic attraction’ between the stylus and the path. In this context, the best way to perform the task is to be compliant to the path, that is, to let the path to which the stylus is magnetically held lead the movement. This enables users to acquire better compliance control gradually because the level of attraction can be gradually reduced. The hope is that the improved compliance control positively transfers to other tasks, such as 2D tracing or drawing tasks, that require good compliance control (for discussion, see Snapp-Childs et al., 2013b).

Previously, we tested this method with 7–8 year old children diagnosed as having Developmental Coordination Disorder (DCD), comparing their learning and performance with age-matched typically developing children (Snapp-Childs et al., 2013b). We also tested and compared 7–8 and 10–12 year old school children. Prior to training, we found that the children with DCD were significantly worse at the 3D tracing task than the age-matched typically developing children. Likewise, the younger school children were worse relative to the older children. After training, the children with DCD performed as well as the typically

developing children who had also trained. Similarly, younger children performed at the same level as older children after training. These results stand apart from those of other studies in two ways related to learning.

First, previous work has shown impaired learning for children with motor difficulties. For example, Zwicker and collaborators (Zwicker Missiuna, Harris, & Boyd, 2011) had children (8 – 12 year old) with motor difficulties (specifically, children with DCD) and typically developing children practice a trail-tracing task and measured the brain activity associated with this practice. Overall, they found that the children with motor difficulties did not improve in the trail-tracing task as much as the typically developing children (and also had under-activation in certain brain regions that have been associated with visual-spatial learning). Likewise, Huau and collaborators (Huau, Velay, & Jover, 2015) showed that (8 – 10 year old) children with motor difficulties (specifically, children identified as having DCD) did not learn how to write a new letter as well as typically developing children. Second, previous work shows that when children with motor difficulties (specifically, children with suspected/probable Developmental Coordination Disorder or those identified as having DCD) exhibit learning, they are still impaired relative to typically developing children. For example, Missiuna (1994) trained children (6.5 – 8.5 years old) with and without DCD to perform aiming movements. All children learned the task but there were persistent differences between children with DCD and typically-developing children – training did not erase differences between the groups. Jelsma and collaborators (Jelsma, Geuze, Mombarg, & Smits-Engelsman, 2014) implemented an intervention for 6–12 year old children with motor difficulties (probable DCD). The intervention was successful in that training with the Wii Fit improved motor performance on the (Wii Fit) ski slalom game; however, because the typically-developing children participating in this study were not trained (or re-tested) it is not possible to determine if equal training resulted in similar or dissimilar gains.

In addition to examining learning of the task, we tested typically developing 7–8 and 10–12 year old school children to see whether training on the 3D tracing task would positively transfer to a 2D drawing task (Snapp-Childs et al., 2014; Snapp-Childs et al., 2015). First, we found a direct relationship between the scale of the reproduced shapes and the amount of spatial error in reproducing the target shape (i.e. copied shapes that were too large had large amounts of spatial error). Second, we found small but significant reductions in the shape errors that the children generated after training – the training positively transferred to the drawing task. This is impressive given that many previous studies have failed to demonstrate transfer to drawing/handwriting tasks (for a review, see Hoy, Egan, & Feder, 2011).

1.1 Present study

The purpose of this study was to examine the efficacy of our training for children with motor difficulties over a range of ages from 5 to 11 years old. We previously tested children diagnosed with DCD, but only at ages 7–8 years of age and we had not tested transfer from the 3D training task to a 2D drawing task. Here we ask whether the training yields improvements in drawing for children with motor difficulties typical of DCD. Also, we previously found age differences (7–8 years old versus 10–12 years old) in pre-training

performance in typically developing children and that age differences were eliminated by training. The question is whether we would now find such age differences in pre-training performance for children with motor difficulties typical of DCD. If so, would the training also eliminate such differences? In sum, we investigated whether children with motor difficulties at various ages would respond to the training as had the typically developing children previously tested. To do this, we examined both training in the 3D tracing task and transfer of that training to a 2D drawing task.

In this study, we also used a cross-over design which allows different sets of participants from the same population with similar characteristics to serve as controls for the training. The participants were divided into two groups and, during specific periods, one group was trained while the other was not, and visa versa. We implemented a cross-over design to enable us to answer questions which we were not previously able to answer. Our work with adults (Snapp-Childs et al., 2013a) revealed that the act of performing the assessment trials (e.g. baseline) is training. For high functioning adults, this limited training was enough to foster significant improvement on the practiced (3D tracing) paths, but not enough to transfer to novel and more difficult paths. Do the children in the current study exhibit improvement given the limited practice that performing the assessment trials provide? If so, does this limited practice yield improvements in 2D drawing?

1.1.1 Predictions—We predicted that, before training, older children would exhibit superior performance relative to younger children. Nevertheless, all children were expected to improve in the training task so that, after training, all children would perform at a similar level of mastery on the 3D tracing tasks. We further predicted all children to exhibit improvement in 2D figure copying (drawing) as a result of having trained in the 3D tracing task as was shown in our previous work (Snapp-Childs et al., 2014; Snapp-Childs et al., 2015). In respect to the control aspect of the cross-over design, we predicted that periods of no training (in the 3D tracing task) would yield no improvements in 3D tracing as well as no transfer to the 2D drawing task.

2. METHODS

2.1 Participants

Fifty-one, 5–11 year old, children were recruited from a primary school in the city of Bradford (West Yorkshire, UK). The school was comparable to the national averages in terms of academic attainment, attendance and proportion of pupils receiving free school meals (a proxy indicator of social deprivation). The majority of pupils were either or White British or Pakistani heritage, with roughly even proportions of each. All of the children in this study were recommended for inclusion by their teachers due to ‘handwriting difficulties’ and/or fine-motor difficulties and all children scored under the 16th percentile on the manual dexterity section of the Movement Assessment Battery for Children 2nd Edition (Henderson et al., 2007) indicating risk of fine motor deficits.

In this study, we used a cross-over experimental design where during one ‘training period’ one experimental group received training/intervention while the other experimental group did not; then, in the next ‘training period’ the previously untrained experimental group

received the training while the other group did not. There were six participating grade levels; one half of each grade level was assigned to training Group A or B, respectively. The children were assigned to the groups based on their classroom. Children in the same classroom were assigned to the same group in order to minimize disruption to teachers. These classes were then allocated to either group A or group B in order to keep overall numbers and distributions of age as equal as possible. All children completed the training sessions. However, four children were either absent during at least one assessment session or were unable to complete the tasks during an assessment session due to technical difficulties; these children were included in the training but were excluded from our analyses. Table 1 shows the age, MABC-2 percentile, and other characteristics of the participants (that were included in the analyses).

2.2 Ethics Statement

This study was approved by the University of Leeds Ethics and Research committee. The children participated with informed assent with (written) informed consent from their parents/guardians.

2.3 Procedure and Apparatus

All assessments, evaluations, and training took place in a private room at the children's school during the school day. Before the assessment and training of computerized tasks began, the children were evaluated by the experimenters (LH and KS) on the Movement Assessment Battery for Children 2nd Edition (MABC-2) and Beery VMI. All children scored under the 16th percentile on the manual dexterity section. After the children were initially evaluated, they were assigned to training group (Group A or B) based upon their classroom. All children were then assessed with a computerized 3D tracing and 2D drawing tasks. After this 1st assessment, training Group A received training in the form of a 5-week customized perceptuo-motor training program. Then all children were assessed again with the 3D tracing and 2D drawing tasks; this was the 2nd assessment session. Following this, there was a period of 3 weeks during which no training took place. After this period, all children were assessed again with the 3D tracing and 2D drawing tasks; this was the 3rd assessment session. After this 3rd assessment session, training Group B received training in the form a 5-week customized perceptuo-motor training program. Then all children were assessed for a final time with the 3D tracing and 2D drawing tasks; this was the 4th assessment session.

2.3.1 3D tracing—The 3D tracing task was similar to that described and used in previous studies (Snapp-Childs et al., 2013a, Snapp-Childs et al., 2013b, Snapp-Childs et al., 2014, Snapp-Childs et al., 2015). In this task, participants performed variations of the same three-dimensional tracing task while seated. The task was to push a (virtual) brightly colored fish along a curved path from a starting to a finishing point (a checkered square) while racing a competitor fish. The participants grasped a stylus that was attached to a desktop force feedback haptic virtual reality device (PHANTOM Omni from Sensable Technologies) and computer (shown in Figure 1a) and used the stylus to feel the wire path and push the fish.

The PHANTOM is an impedance control device. The user moves the stylus and the device reacts with a force if a virtual object is encountered. Thus, the PHANTOM has displacement as an input and force as an output. The mass and friction of the PHANTOM has been made small by careful mechanical design. In this experiment, participants could “feel” the 3D path once they encountered it. Phenomenologically, it was as if the stylus was “magnetically attracted” to the path¹. The curved paths were inspired by and, therefore, similar to a ‘bead maze’. These toys are commonly found in pediatrician waiting rooms and consist of brightly colored curved ‘roller coaster’ wires with beads on them that can be pushed along the wires by a child. Using a stylus to push the bead along the wire would be, and is for our task, very difficult because the stylus tends to come off the path. Hence, for our task, the path ‘magnetically attracted’ the stylus to hold it on the path. The ‘magnetic strength’ was parametrically varied in order to alter task difficulty (the highest levels of support/attraction were easy and the lowest levels of support/attraction were difficult). At the assessment sessions, participants attempted two trials at each of six levels of support (‘magnetic attraction’), on the path pictured in Figure 1. They were instructed to 1) trace the entire path with their fish, while 2) racing and ‘beating’ a competitor fish that took 20s to travel the path from start to finish. Trials were automatically terminated after 90s if the child failed to complete the path.

2.3.2 Drawing—In the drawing test, participants were seated at a table in front of a tablet PC (Toshiba Portégé M750 tablet PC, screen size 163 mm by 260 mm, using customized software to manage stimulus presentation, user interface, and data collection as described by Culmer and collaborators (Culmer, Levesley, Mon-Williams, & Williams, 2009). The task was to view a figure, then to copy (not trace) the figure on the computer screen using a handheld stylus in the dominant hand. At the beginning of each trial, the upper half of the screen contained a black rectangular frame (12 × 6.5 cm) around a black line form and the lower half of the screen contained a green rectangle of equal dimensions to the black frame. Participants looked at the figure inside the black frame then placed the hand held stylus on the green rectangle at the location where they would start copying the figure (for an illustration, see Snapp-Childs et al., 2014). Once the stylus was inside the rectangle for 200 ms, the green rectangle disappeared and was replaced with a white rectangle (same color as the background) with a black border around it (note that this was similar to the rectangle in the upper portion of the screen containing the to be copied figure). Any given trial was terminated when a virtual button (which appeared once participants began to draw the form) in the upper right-hand corner of the screen was pressed. After this (virtual) button was pressed, the next trial automatically started.

Participants performed three practice trials to become familiar with the task and interface (a horizontal line segment, one cycle of a sine wave, and a circle); these trials were not analyzed. Then, participants completed two repetitions of each of nine forms (shown in Figure 1e), for a total of eighteen trials. The forms were of three figure types with three

¹The force pulling the stylus was modeled as a virtual spring where the stiffness of the spring could be altered. The spring had a virtual length of ≈0.5cm from the center of the path so the force dropped to zero if the stylus moved >0.5cm from the path. The spring stiffness (and consequently the level of “attraction” or support) was parametrically varied to alter task difficulty. The forces pulling the stylus towards the spring were set at six different levels corresponding to forces of approximately 2.02N, 1.08N, 0.83N, 0.57N, 0.35N and 0.13N.

examples of each type. The first type was basic (circle, square, and triangle). The second type was spiral (circular, square, and triangular spirals). The third type was wave. Each wave consisted of three sinusoidal cycles. The first was of constant amplitude with a height of 46 mm. In the second wave, the amplitude varied over the cycles in respect to the top of each cycle, but not the bottom where each cycle touched the baseline. The heights were 16, 46, and 16 mm. The third was similar to the second except that the small amplitude cycles were centered vertically while the tops and bottoms of each cycle varied.

3.2.3 Training—The training program consisted of five roughly 20-minute training sessions that were separated by approximately one week. Participants performed a series of 3D tracing tasks that varied in length, curvature, and torsion (see Figure 1b, c, d) where they raced against two different competitors; one competitor completed the path in 25s while the other completed the path in 15s. The first training session started with the highest level of support (‘magnetic attraction’), slowest competitor, and shortest path. The participant was required to “beat” the slowest competitor two times-in-a-row in order to progress to the faster competitor². After the participant beat both the slower and faster competitors, they then moved to the next longest path with slowest competitor. After all paths and competitors were “beaten”, the level of support was decreased and the participant re-started with the shortest path and slowest competitor. In order to prevent extreme frustration, if a child was not able to “beat” a particular path/level/competitor combination two-times-in-a-row within six attempts, the child was automatically advanced to the next combination.

2.4 Data analysis

As mentioned previously, half of the children were trained during the 1st training period (Group A) and the other half were trained during the 2nd training period (Group B). Due to the small number of children participating in each grade level and training group, we combined the first three grade levels as younger children and the upper three grade levels as older children resulting in four experimental groups (Group A – younger children, Group B – younger children, Group A – older children, Group B – older children; see Table 1).

2.4.1 3D tracing—The three-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, trial duration was computed as a temporal measure of performance. Trial duration was the time it took for a trial to be completed (the time in seconds from when participants arrived at the starting location to when they arrived at the finish marker). We selected duration because it provides a single unambiguous global measure of performance that related directly to the explicitly stated goal of the task and because it is often used as a performance measure in a wide range of motor tasks. In previous studies, we had also used other spatial measures, but analyses showed these to be redundant with duration.

²The 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 “two-wins-in-a-row” rule to determine when the children progressed.

2.4.2 Drawing—The two-dimensional coordinates of the stylus were recorded at 120 Hz. These data were filtered using a dual-pass, second order Butterworth filter with a 10 Hz cut-off frequency. We calculated two variables for each of the forms that participants produced: the scale factor and shape error (this was previously referred to as ‘shape accuracy’ (Culmer et al., 2009; see Snapp-Childs et al., 2014 for illustration. To do this, we used a technique called ‘point-set registration’. In this technique, point-sets were generated for the participant-generated paths and reference paths by resampling the spatial coordinates, using linear interpolation, at a resolution of 1 mm. We then used a robust point-registration method (Snapp-Childs et al., 2014) to determine the transformation that makes the participant-generated path most closely match the reference path. The transformation consisted of translation, rotation and isotropic scaling components. Scale factor is the isotropic scaling component of the transformation; that is, scale factor is how much growing or shrinking is required to make the participant-generated paths best match the size of the reference paths i.e. an oversized participant-generated path results in a scale factor < 1. Shape error was calculated by evaluating the mean distance between corresponding points on the transformed input path and the reference path and, thus, represents how well the participant was able to recreate the qualitative properties of the form irrespective of input scale, location or rotation errors.

2.4.2 Statistical analyses—We calculated the median duration (3D tracing tasks) and shape error (2D drawing tasks) separately for each participant, over the trials performed in a given condition (3D tracing: level of spring stiffness; 2D drawing: figure type) and session (assessments 1 – 4). Statistical analyses of the group differences and changes of these measures were performed with repeated measures (mixed design) analysis of variance. For these analyses, age (5–8 years old, 8.5–11 years old) and/or training group (A or B) were between-subjects factors and session/learning (assessment 1 – 4) and support level (3D tracing: that is, level of spring stiffness which varied from 0.13N to 2.02N) and figure type (2D tracing) were within-subjects factors. Significant levels were set at $\alpha = .05$ for all statistical analyses. For significant factors, we report generalized eta-squared (η^2) measure of effect size.

Our statistical analyses of both the 3D tracing and 2D drawing tasks followed the same sequence. First, as is typical of studies involving children of various ages, we expected to find age-related difference in performance prior to training (performance at the 1st assessment). So, we examined whether or not there were age differences with respect to performance before training. Second, we examined whether or not the children improved given equivalent amounts of training/testing (improvement from the 1st to 4th assessment). Then we explored the amount of improvement explicitly due to training (improvement from the 1st to 2nd assessment for Group A, improvement from the 3rd to 4th assessment for Group B). Finally, we examined changes in performance without (explicit) training as a control.

This last set of analyses was necessary because a previous study of this training method and 3D tracing task revealed a problem in that the performance during the non-training sessions (that is, baseline, posttest, etc.) is a weak form of training (Snapp-Childs et al., 2013a). In our previous work with adults a control group was included that received no explicit training, but they exhibited improvement in performance between baseline and post-test

merely because the task in these session necessarily afforded some training. To address this problem, we performed the following analyses. First, we combined Groups A and B and compared baseline (assessment 1) to the final post-test (assessment 4). In this comparison, all participants experienced exactly the same non-training (assessment 1-4) and training sessions. Second, we assessed the effect only of training as such by combining and comparing assessment 1 and 2 for Group A and assessment 3 and 4 for Group B. Third, we tested the effect of the longer duration intervals that were without training by combining and comparing assessment 3 and 4 for Group A and assessment 1 and 2 for Group B. We had to expect some improvement in performance simply because the assessment sessions afforded training, although we expected much less improvement than found as a result of the explicit training just as had been found by Snapp-Childs and collaborators (Snapp-Childs et al., 2013a). We included group as a factor only when the number of sessions was the same for both groups, and not otherwise. Finally, we preceded these analyses with an analysis of baseline (assessment 1) to determine that Groups A and B were the same in performance level before training. Again, the pattern of analyses was the same for the 3D tracing task and the 2D drawing task, that is, the transfer task.

3. RESULTS

3.1 3D tracing

3.1.1 Differences before training—To examine whether or not age-related differences in performance before training exist, we performed a mixed design ANOVA on duration (at assessment 1 only) with age (5–8 vs. 8.5–11) and training group (A vs. B) as a between-subjects factors and support level (1-6) as a within-subjects factor. The result yielded a main effect of level [$F(5, 215) = 60.2, p < .001; \eta^2 = 0.42$] but no effect of age or training group and no significant interactions ($p > .1$). In sum, there were no age differences in the initial performance in the 3D tracing task.

3.1.2 Overall improvement—To examine whether or not the children improved given equivalent amounts of training/testing, we tested durations both before and after both training periods (i.e. assessment 1 versus 4). To do this, we performed a mixed design ANOVA with training group (A or B) and age (younger vs. older) as a between-subjects factors, and session (assessment 1 and assessment 4) and level of support (1 - 6) as within-subjects factors. Only session [$F(1, 43) = 231.0, p < .001; \eta^2 = 0.49$] and level of support [$F(5, 215) = 89.4, p < .001; \eta^2 = 0.34$] yielded main effects. There was also a session by level of support interaction [$F(5, 215) = 23.0, p < .001; \eta^2 = 0.13$]; this interaction was due to the greater improvement with lower levels of support from assessment 1 to assessment 4. Neither age nor training group nor any interactions with training group was significant ($p > .10$). As shown in Figure 2, performance was better after training and with higher levels of support.

3.1.3 Improvement explicitly due to training—To examine whether or not the children improved comparing assessment performance directly before training to directly after training, we performed a mixed design ANOVA with age (younger vs. older) as a between-subjects factor, and session (assessment 1 and 2 for Group A, assessment 3 and 4

for Group B) and level of support (1 - 6) as within-subjects factors. Session [$F(1, 45) = 94.8$, $p < .001$; $\eta^2 = 0.33$] and level [$F(5, 225) = 95.6$, $p < .001$; $\eta^2 = 0.31$] yielded main effects. There was also a session by level of support interaction [$F(5, 225) = 27.4$, $p < .001$; $\eta^2 = 0.11$]; this interaction was due to the greater improvement with lower levels of support from first to the second relevant assessment (again, assessment 1 and 2 for Group A, assessment 3 and 4 for Group B). A main effect of age was not found ($p > .10$). No other interactions were significant ($p > .10$). These results essentially replicate what was shown for overall improvement.

3.1.4 Changes without (explicit) training—To examine if the children in the current study exhibited improvement given the limited practice that performing the assessment trials provide, we tested the changes in trial duration during the times when the groups were not being trained. To do this, we performed a mixed design ANOVA with age (younger vs. older) as a between-subjects factor, and session (assessment 3 and 4 for Group A, assessment 1 and 2 for Group B) and level of support (1 - 6) as within-subjects factors. Session [$F(1, 45) = 7.7$, $p < .001$; $\eta^2 = 0.01$] and level of support [$F(5, 225) = 44.4$, $p < .001$; $\eta^2 = 0.20$] yielded main effects. There was a significant age by session interaction [$F(1, 45) = 9.0$, $p = .004$; $\eta^2 = 0.01$], but no main effect of age ($p > .10$). No other interactions were significant ($p > .10$). Thus, as we previously found with adults, minimal practice did yield some improvement in performance by these children on the 3D tracing task.

However, the younger children exhibited less improvement than did the older children. Furthermore, the magnitude of improvement was smaller without explicit training than with it. To illustrate this we, calculated improvement for the lowest level of support for the trained and untrained periods for each group. We then performed a paired t-test comparing trained and untrained periods separately for each group. For Group A, the improvement with training was significantly larger than without training (mean difference = 42.1 s; $t(22) = 6.4$, $p < .001$) as it was for Group B, (mean difference = 16.3 s; $t(23) = 3.1$, $p = .006$). Group B had more assessment sessions before explicit training (3 versus only 1) and thus, had more (implicit) training.

3.2 2D drawing

3.2.1 Differences before training—We predicted that we would find age differences with respect to shape error as well as differences between figure types but no differences between training groups (A vs. B) prior to training. To test these predictions, we performed a mixed design ANOVA on shape error with age (younger vs. older) and group (A vs. B) as between-subjects factors and figure type (simple, spiral, wave) as a within-subjects factor. The result yielded a main effect of age [$F(1, 43) = 38.6$, $p < .001$; $\eta^2 = 0.25$] and figure type [$F(2, 86) = 96.0$, $p < .001$; $\eta^2 = 0.58$] as well as an age by figure type interaction [$F(2, 86) = 4.7$, $p = 0.01$; $\eta^2 = 0.06$], but no effect of training group and no significant interactions with training group ($p > .1$). Errors were greater for younger children and for wave type figures; the age by figure type interaction reflects that the younger children produced larger errors for the waves than did the older children.

3.2.2 Overall improvement—To examine whether or not the children improved in drawing given equivalent amounts of training/testing in the 3D tracing task, we performed a mixed design ANOVA on the shape error scores with training group (A or B) and age (younger vs. older) as between-subjects factors, and learning (assessment 1 and assessment 4) and figure type (simple, spiral, wave) as within-subjects factors. Only session [$F(1, 43) = 9.15, p = .004; \eta^2 = 0.03$], age [$F(1, 43) = 41.3, p < .001; \eta^2 = 0.22$], and figure type [$F(2, 86) = 154.3, p < .001; \eta^2 = 0.56$] yielded main effects; there was also an age by figure type interaction [$F(2, 86) = 7.9, p < .001; \eta^2 = 0.06$]. Neither training group nor any interactions with training group was significant ($p > .1$). As shown in Figure 3, the overall level of error was lower after training (see Figure 3c) but varied with figure type and age. Copies of the simple figures were most accurate, then copies of spirals, and copies of the waves were least accurate (see Figure 3b). As might be expected, older children produced figures with less error compared to younger children (see Figure 3a).

3.2.3 Improvement explicitly due to training—We examined whether or not the children exhibited improved shape error scores comparing performance directly before training and directly after training by we performed a mixed design ANOVA with age (younger vs. older) as a between-subjects factor, and learning (assessment 1 and 2 for Group A, assessment 3 and 4 for Group B) and figure type (simple, spiral, wave) as within-subjects factors. Learning [$F(1, 45) = 5.4, p = .03; \eta^2 = 0.01$], age [$F(1, 45) = 37.5, p < .001; \eta^2 = 0.23$], and figure type [$F(2, 90) = 147.4, p < .001; \eta^2 = 0.54$] yielded main effects. There was also an age by figure type interaction [$F(2, 90) = 7.6, p < .001; \eta^2 = 0.06$]; this reflects that the younger children produced more errors for the wave figures than did the older children. No other interactions were significant ($p > .1$). The overall level of error was lower after training but varied with figure type and age. Copies of the simple figures were most accurate, then copies of spirals, and copies of the waves were least accurate. Again, older children produced figures with less error compared to younger children. Younger children improved more in drawing the basic figures while older children improved more in drawing the more difficult wave figures.

3.2.4 Changes without (explicit) training—The 3D tracing task was designed as a training task with modulated levels of support that were tested during both assessment and training sessions. Unlike this, the 2D drawing task was designed to test transfer of the training. Significant change in performance was not expected as a result of performance during assessment sessions. We examined whether the passage of developmental time between assessment sessions improved drawing performance and reduced shape errors. We tested the changes in shape error during the times when the groups were not being trained. To do this, we performed a mixed design ANOVA with age (younger vs. older) as a between-subjects factor, and session (assessment 3 and 4 for Group A, assessment 1 and 2 for Group B) and figure type (simple, spiral, wave) as within-subjects factors. Age [$F(1, 45) = 26.2, p < .001; \eta^2 = 0.16$] and figure type [$F(2, 90) = 99.8, p < .001; \eta^2 = 0.48$] yielded main effects, but, session did not ($p > .05$). There were no significant interactions ($p > .1$). Thus, without training, there were no changes in performance.

3.2.5 Influence of novelty—The technology used in this study (and in our previous work) is unusual and novel, at least from the perspective of a school-aged child. It is possible that, given the novelty, participants might improve on the tasks just because the task is no longer novel. To assess this possibility, we examined the improvement from the 1st to the 2nd assessment sessions for Group B (untrained) alone. We predicted that there would be no improvement, and thus, no ‘novelty effect’. To do this, we performed a mixed design ANOVA with age (younger vs. older) as a between-subjects factor, and session (assessment 1 vs. assessment 2) and figure type (simple, spiral, wave) as within-subjects factors. There were main effects of age [$F(1, 21) = 33.1, p < .001; \eta^2 = 0.23$] and figure type [$F(2, 42) = 57.9, p < .001; \eta^2 = 0.55$], but neither session nor any interactions were significant ($p > .05$). Thus, there was no effect of task novelty on the drawing task.

4. DISCUSSION

The goal of the present study was to examine the efficacy of our training method for children of a wide range of ages who were identified as having handwriting difficulties and/or motor impairments. Previously, Snapp-Childs and collaborators (Snapp-Childs et al., 2013b) developed a method for training manual compliance control in children. First, children with Developmental Coordination Disorder (DCD) were trained using the method. Like in this study, before training, the task was exceptionally difficult for the children to perform without strong support. After training, however, they could do the task as well as typically developing children even at very low levels of support. Next, Snapp-Childs et al. (2014) trained typically developing 7–8 year old children on the 3D tracing task and found that the training transferred to a 2D drawing task. Snapp-Childs et al. (2015) found the same with 10–12 year old children. Moreover, when comparing the performance on the 3D tracing task, Snapp-Childs et al. (2015) found initial age differences between the (typically developing) 7–8 and 10–12 year olds and that these differences were eliminated following training. Here, we investigated whether we would find a similar pattern of results in a population of children with motor difficulties by comparing the performance in the new training method of children in two different age groups, namely, 5–8 years of age and 8.5–11 years of age. Also, although Snapp-Childs and collaborators (Snapp-Childs et al., 2013b) had previously tested the efficacy of the training with children diagnosed with DCD, transfer to the 2D drawing task was not tested. So, we now investigated whether the training would so transfer for children with motor difficulties at a wide range of ages. We found that: 1) older children initially performed better than younger children only on the 2D drawing task, not on the 3D tracing task; 2) initial performance in the 3D tracing task by these children with motor difficulties was worse than that of previously tested school children without motor difficulties and comparable to previously tested children diagnosed with DCD; 3) training on the 3D tracing task yielded improvements on the 3D tracing task, regardless of age; 4) training on the 3D tracing task yielded improvements on a 2D drawing task; and 5) training on the 3D tracing task did not eliminate age differences on the 2D drawing tasks.

4.1 Learning in children with motor difficulties

There is a fairly persistent belief that children with motor difficulties (e.g. suspected, probable, or diagnosed Developmental Coordination Disorder) have difficulties learning new

motor skills. Indeed, there is evidence to support this view (e.g. Huau et al., 2015; Zwicker et al., 2011). At the same time, however, there is ample evidence that certain therapies and interventions can be effective and clearly yield learning in children with motor difficulties (including the results from the present study along with Jelsma et al., 2014; Missiuna, 1994; and Snapp-Childs et al., 2013). So why do children with motor difficulties show learning in some studies and not in others? We believe that a partial explanation lies in the ‘softer’ aspects of the to-be-learned tasks. Jelsma and collaborators trained children with motor difficulties using a Wii Fit – a gaming system that was designed to be entertaining and enjoyable. Similarly, our system involves light competition/racing and was designed to be enjoyable (and appropriate for children with motor difficulties). Jelsma and collaborators documented their participants’ attitudes/feelings using an emoji-based enjoyment scale. They showed that most children continued to enjoy the tasks for the duration of the intervention. This was an important finding because the training task was relatively difficult for the children (with motor difficulties) to perform and children typically become averse to interventions if they are too challenging. Our approach, however, was designed to keep enjoyment and self-efficacy high throughout the intervention by keeping levels of performance relative high; thus, avoiding the aversion in the first place (Snapp-Childs et al., 2016).

4.2 Only some age-related differences

Again, one of the most common findings in developmental studies is that older children outperform younger children. We found age differences, which persevered despite training, on the 2D drawing tasks. However, we found no age differences on the 3D tracing task prior to training (and after explicit training). This was surprising because, again, it is the norm to find age related differences in children of this age range and also because we previously found age differences on this same task (e.g. see Snapp-Childs et al. 2015). One explanation for the lack of age differences (prior to training) is that the older groups had more females – that is, there was a gender imbalance with respect to age. It is possible that the younger group performed better than expected because of the higher proportion of males i.e. there was ‘male advantage’ for the younger group. We, however, doubt that our current age result is due to gender differences. The evidence for gender-based advantages is mixed – on the one hand, there are ‘male advantages’ in throwing, navigation, and mental rotation tasks (e.g. see Nelson, Thomas, & Nelson, 1991; Astur, Tropp, Sava, Constable, & Markus, 2004; Grön, Wunderlich, Spitzer, Tomczak, & Riepe, 2000) but, on the other hand, there is evidence for ‘female advantage’ in handwriting tasks (e.g. see Frith & Vargha-Khadem, 2001; Ziviani & Elkins, 1984). Gender differences in motor performance (and learning) appear to be highly dependent on the nature of the task. So, instead, we suspect that the lack of age differences is due to the population studied here, namely, children with handwriting and/or fine motor difficulties.

It is possible that relatively poor manual dexterity exhibited by the entire population in this study interacted with the relatively difficult nature of the 3D tracing tasks (especially with low support) and the resulting poor and variable performance masked any age related differences. This interpretation is consistent with the Dynamics Systems perspective as outlined by Thelen and Smith (1994). From a Dynamic Systems perspective, behavioral

patterns are believed to exist and change because many factors cooperate and interact with each other; this is in contrast to the belief that age-related superiority is due to the relatively advanced status of the nervous system i.e. maturation. Rather, behaviors are *emergent*. Behaviors arise as a result of the tensions between the characteristics of the individual – including, but not limited to, motor capabilities – and the constraints that the environment and task place on the individual (Corbetta, Thelen, & Johnson, 2000). The constraints that the 3D tasks placed on these children were high. Thus, in contrast to previous work, none of the children could initially produce advanced levels of performance; in fact, their initial performance was quite the opposite. However, as before, the children were able to improve with the training method.

4.3 What did the training do for children i.e. why is the training effective?

We believe that control of limb compliance is at the root of good performance on a variety of fine motor tasks like drawing and handwriting. The training method that we employed here, and in previous studies, enables children to better control their upper limbs particularly when tracing complex 3D paths or when copying 2D figures because those actions require continuous monitoring and adjusting of the stiffness of the limb. One other thing to note about both the tasks employed here is the very strong role of spatial accuracy demands. In the 3D tracing tasks, it was essential to be accurate spatially – and increasing spatial accuracy enabled increasing temporal efficiency. In the 2D drawing task, the children were under no time pressure to complete these tasks thus allowing them to focus on the spatial aspects. Nevertheless, the 3D tracing training transferred to the 2D drawing task resulting in about a 10% reduction in shape error.

It is important to note that a 10% reduction in shape error is significant. The children only practiced the 3D tracing task for about 20 minutes once a week for 5 weeks, that is, for a total of less than 2 hours. These are good gains for such small investment in time. Previously, we found that typically developing children who performed poorly on the Visual Perceptual (VP) section of the Beery VMI showed smaller improvements on a similar set of 2D drawing tasks than their peers who scored highly (see Snapp-Childs et al., 2014). So, it was possible that the children in this study would show very little to no improvement on the 2D drawing tasks given that they were not typically developing children and performed relatively poorly on the VP portion of the Beery VMI (less than 25% of students scored above the 50th percentile). Moreover, in this study, we employed a cross-over design thus allowing us to empirically demonstrate that simply becoming 5-6 weeks older (the length of the training period) did not lead to improvements in 2D drawing performance.

4.4 Does haptic guidance help learning (the most)?

The process of learning a new skill has been characterized as a matter of producing a rough approximation of the movements first then refining the qualitatively correct but quantitatively lacking movements (Newell, 1991; Swinnen, 1996); subsequent quantitative improvement follows with extensive practice. The best approach to foster either qualitative or quantitative improvement remains unclear or is, at least, controversial. In the current study, we have provided *haptic guidance* (Williams & Carnahan, 2014). By this, we mean that we reduce the tendency of the learners (children) to make errors – at least initially. As

the training proceeds, it becomes easier to generate errors but by having experienced previous errors, the learners are better able to generate corrections. The results from the present study are in agreement with work from a variety of disciplines (e.g. Feygin, Keehner, & Tendick, 2002; Grindlay, 2008) that indicates that haptic guidance is beneficial for skill learning. However, is it the most beneficial?

A potentially more beneficial approach is to learn with *error-augmentation*. Williams and Carnahan (2014) proposed that error-augmentation could be advantageous because learning is driven by errors both directly and indirectly (i.e. as a motivational tool). As a whole, we agree with the idea that error drives learning. However, there are limits to this notion. Snapp-Childs, Wang and Bingham (2016) demonstrated that generating a high number of errors during training led to good learning but not better learning than when generating a moderate number of errors – and contrary to Williams and Carnahan's assertions, generating more errors did not appear to “speed up” learning. In fact, even when training young, healthy adults (as in Snapp-Childs et al., 2015), more errors appeared to be more of a nuisance during training rather than a learning booster. Instead, this work demonstrated that training results in learning to be more compliant and having improved prospective control so that participants do not generate errors in the first place. Thus, we believe that limits to the number of errors are important especially when working with children and even more so when training individuals with motor impairments.

4.5 Conclusions

Previously, we likened our training method to the *enculturated interactions* (Adolph & Robinson, 2015) where being exposed to a specific set of experiences affects the emergence of developmental milestones and can advance achievements. The training was certainly moving children in the right direction and, therefore, can be used along with other resources to provide an intervention to children who have or are at risk of having motor difficulties. In sum, this approach to training is showing good promise as a means to help children with or without motor difficulties to improve in performance of fine motor manual tasks like drawing or potentially, handwriting. These results further indicate that the training methods and materials are well suited to be applied within schools.

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7. APPENDIX

Previously, when testing school children, we found a difference in the pre-training or baseline level of performance in the 3D tracing task as a function of age. The children in the current study all exhibited motor difficulties and we failed to find the expected age dependent differences in initial performance. Given this lack of expected age difference before training, we compared the pre-training performance of these children to those in our previous studies to determine how similar these children were both to the school children previously tested (data originally reported in Snapp-Childs et al., 2014) and the children with DCD previously tested (data originally reported in Snapp-Childs et al., 2013b). To do

this we performed separate mixed design ANOVAs with group (children in this study vs. DCD or TD 7–8 years olds) as a between-subjects factor and level of support (1 - 6) as a within-subjects factor. For the comparison of children in this study versus the children with DCD, there was only a main effect of level of support [$F(5, 265)=75.7, p < .001; \eta^2 = 0.42$]. There was no effect of group (or group by level of support interaction; $p > .1$), meaning that the children in this study performed similarly to the children with DCD in our previous work.

For the comparison of children in this study versus the school children without motor difficulties, there was a main effect of level of support [$F(5, 340)=87.4, p < .001; \eta^2 = 0.40$] and of group [$F(1, 68)=21.5, p < .001; \eta^2 = 0.13$], but no interaction ($p > .05$). Hence, the children in this study performed differently than 7–8 year old school children without motor difficulties and in particular, they performed less well. Snapp-Childs et al. (2015) found that these 7-8 year old school children performed significantly less well at baseline than 10-12 year old school children. Given that the current group of 5-11 year olds performed less well at baseline than the 7-8 year olds, then they were definitely also performing less well than the 10-12 year olds. These children with motor difficulties were all just performing less well at baseline and thus, performing comparably to the children with DCD that we had previously tested. The result was lack of change in baseline performance with age.

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HIGHLIGHTS

- We examined the efficacy of 3D tracing training program for children 5-11 years old with motor difficulties.
- All children initially performed very poorly on the 3D tracing task.
- Training improved performance regardless of age.
- Training on the 3D task positively transferred to a 2D drawing task.

Figure 1.

A) The PHANTOM Omni with the display illustrating the path used in baseline and posttest trials. B), C), D) Illustrations of the paths used in training in the 3D tracing task. E) Illustrations of the nine target forms copied by participants.

Figure 2. Median duration by age group for each support level during the 1st and 4th assessment sessions.

Figure 3. Median shape error for A) younger vs. older children, B) drawings of each of the three types of target figures, and C) before any training and after all training at the 3D tracing task.

Table 1

Age at initial testing (average $\pm$ standard deviation), sex, handedness and score on Movement Assessment Battery for Children 2nd Edition (MABC-2) (average $\pm$ standard deviation), split by age and training group

Group	N	Age (years)	Sex (F, M)	Handedness (R, L)	MABC-2 Manual Dexterity (%ile)	MABC-2 Total (%ile)
A – Younger	11	6.55 $\pm$ 0.87	0, 11	9, 2	5.46 $\pm$ 3.68	8.8 $\pm$ 11.69
B – Younger	10	6.57 $\pm$ 0.93	2, 8	10, 0	5.15 $\pm$ 3.69	10.91 $\pm$ 10.93
A – Older	12	9.27 $\pm$ 1.03	5, 7	11, 1	6.54 $\pm$ 3.31	5.52 $\pm$ 4.34
B – Older	14	9.51 $\pm$ 0.79	8, 6	14, 0	3.32 $\pm$ 2.91	7.43 $\pm$ 16.28

Note: Group A = Received training in Training Period 1 (but not 2); Group B = Received training in Training Period 2 (but not 1)