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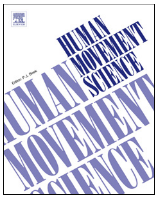

Training children aged 5–10 years in manual compliance control to improve drawing and handwriting

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ABSTRACT

A large proportion of school-aged children exhibit poor drawing and handwriting. This prevalence limits the availability of therapy. We developed an automated method for training improved manual compliance control and relatedly, prospective control of a stylus. The approach included a difficult training task, while providing parametrically modifiable support that enables the children to perform successfully while developing good compliance control. The task was to use a stylus to push a bead along a 3D wire path. Support was provided by making the wire magnetically attractive to the stylus. Support was progressively reduced as 3D tracing performance improved. We report studies that (1) compared performance of Typically Developing (TD) children and children with Developmental Coordination Disorder (DCD), (2) tested training with active versus passive movement, (3) tested progressively reduced versus constant or no support during training, (4) tested children of different ages, (5) tested the transfer of training to a drawing task, (6) tested the specificity of training in respect to the size, shape and dimensionality of figures, and (7) investigated the relevance of the training task to the Beery VMI, an inventory used to diagnose DCD. The findings were as follows. (1) Pre-training performance of TD and DCD children was the same and good with high support but distinct and poor with low support. Support yielded good self-efficacy that motivated training. Post training performance with no support was improved and the same for TD and DCD children. (2) Actively controlled movements were required for improved performance. (3) Progressively reduced support was required for good performance during and after training. (4) Age differences in performance during pre-training were eliminated post-training. (5) Improvements transferred to drawing. (6) There was no evidence of specificity of training in transfer. (7) Disparate Beery scores were reflected in pre-training but not post-training performance. We conclude that the method improves manual compliance control, and more generally, prospective control of movements used in drawing performance.

1. Introduction

Both in the US and the UK, Developmental Coordination Disorder (DCD) is estimated to affect about 1 in 20 children (that is, ≈5–6%), mostly boys (Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001; Kamps, 2005; Polatajko, Fox, & Missiuna, 1995; Sugden, 2006). Accordingly, most classrooms should be expected to include children with this developmental disorder. One of the most reliable effects of DCD is poor fine motor coordination and thus, these children characteristically exhibit very poor handwriting (Smits-Engelsman, Niemeijer, & Galen, 2001). A number of years ago, we set out to develop a training method to enable children to

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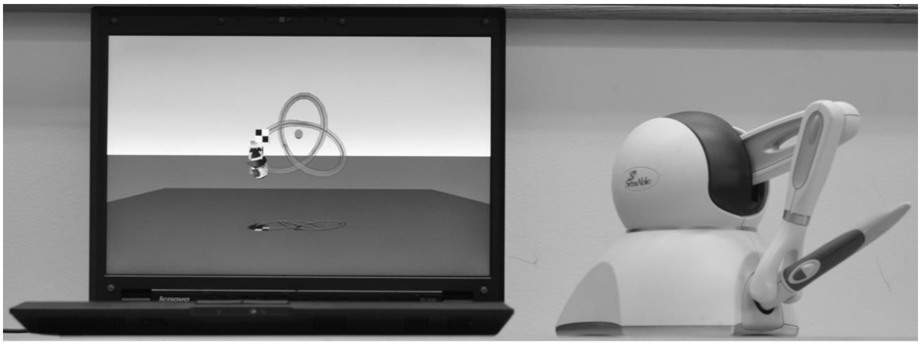

Fig. 1. An example display, showing a wire path, together with a Phantom Omni (Snapp-Childs, Casserly, et al., 2013).

improve their control of a stylus or writing implement when used to draw or write (Snapp-Childs, Mon-Williams, & Bingham, 2013). Such tasks entail manual compliance control. The movement of the stylus is constrained by the surface on which the drawings or letters are made so that the movement trajectories are 2D. Ideally, perceptual control of the movements senses the surface and effectively allows it to help control the movements, simplifying the task. Children with DCD often apply significant force to dig a stylus into a surface on which they write or draw with the result that their hand grows tired and cramped. Thus, their compliance control appears to be less effective than it might be. Compliance control is a form of prospective control, that is, online perceptual guidance and control of a trajectory that anticipates the required trajectory (Dessing, Bullock, Peper, & Beek, 2002; Hogan, 1985, 1990; Snapp-Childs, Casserly, Mon-Williams, & Bingham, 2013; Von Hofsten, 1993).

We developed our training method with a number of different goals in mind. Given the prevalence of DCD, there is a relative dearth of therapists available to help these children. So, a goal was to develop training that could be automated and autonomous, portable and relatively inexpensive, a system that could be used in classrooms, homes and clinics. We developed a task to be performed using a desktop force feedback robotic arm, called the Phantom Omni, coupled with a computer graphics display as shown in Fig. 1. A stylus on the end of the robot arm controls a virtual stylus that is visible in the display and that moves in the computer graphics environment just as does the Phantom stylus held in the hand. The basic task is to use the stylus to push a fish shaped bead along a wire and around its complex curved 3D path and to do so in as short a time as possible. The task features skilled manual compliance control to allow the wire to guide the stylus along the path. This is a task that children with DCD would find to be nearly impossible to do, struggling to keep the stylus on the wire behind the bead while negotiating the complexly curved path. So, a second goal, primary to the training, was to improve manual compliance control, and relatedly, prospective control of the trajectory.

Related to this, a third goal was to solve a “catch-22” problem faced by these children. Newell (1991) described motor learning has having two stages. First, the learner acquires a qualitative approximation to the movements to be learned. Once this is achieved, the learner can then 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. To try to solve this problem for these children, we provided parametrically modifiable levels of support to their performance of the 3D tracing task during training. The support was formulated to solve the compliance control problem for these children during the early stages of learning. If successful, it should make the performance of the children with DCD indistinguishable from that of typically developing (TD) children. Enabling the children with DCD to perform well in this way, in turn, would achieve the next goal in our training and that is to yield good self-efficacy for the children as they train at the task. Good self-efficacy typically yields strong motivation for training by making it rewarding for the children. The method for providing support for good performance of the 3D tracing task was to make the wire magnetically attractive to the stylus. With strong magnetic attraction (that is, high support) the stylus is held onto the wire and the performer only needs to then move the stylus along the wire allowing the wire to lead the movement. This is exactly what we wanted the children to become skilled at doing. In training, as the children improved in performance, the level of support was gradually reduced, maintaining good self-efficacy all the while, until finally, the children might be able to perform the task without support and do it as well as TD children. Before training, high support should make DCD and TD children look the same while low support should reveal the differences between them in respect to their ability to manually control movements of the stylus relative to a constraint surface. After training, both DCD and TD children should have improved significantly in their levels of performance that, in turn, should be the same, with or without support. These were the goals of our training method.

2. Testing the method with DCD and TD children

Snapp-Childs et al. (2013) tested this training method comparing pre- and post-training performance of eight children diagnosed as DCD with that of eight TD children. All of the children were 7–8 years old. As shown in Fig. 2, pre-training performance reflected the level of support in both groups of participants. With a high level of support, performance was equally good for both groups. Mean time to traverse the wire path was ≈10 s. With the lowest level of support, the two groups were strongly distinguished. Mean time to completion was ≈33 s for TD children and over 65 s for children with DCD. Many trials performed by children with DCD simply had to be terminated because the children could not complete the path. Participants trained once a week for 5 weeks over sessions that

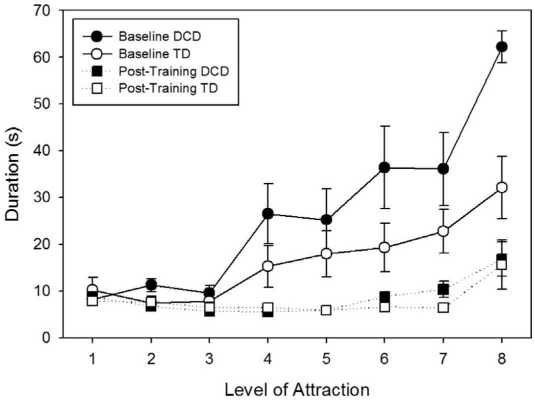

Fig. 2. Mean durations plotted as a function of level of attraction (or support) (1 = high attraction, 8 = low attraction) for the TD and DCD groups both pre- and post-training. TD: open symbols. DCD: filled symbols. Pre-training: circles. Post-training: squares. Error bars are standard errors.

took about 20 min. Training started at the highest level of support. Participants first trained to push their fish to the end of the path before a competitor fish that completed the path in 30 s. Then, they trained to beat a 10 s competitor. Once this was achieved, they moved to beat the 30 s competitor on a more difficult path. After beating the fastest competitor on a third and most difficult path, they started again with the slowest fish and easiest path at the next lower level of support. In this way, they worked their way to performance with the lowest level of support, the fastest fish and most difficult path. As shown in Fig. 2, performance in post-training trials was the same for the two groups across support levels, and in particular, at the lowest level of support. Furthermore, performance improved for both groups so as to no longer vary as a function of the level of support (that is, ≈10 s) except at the lowest support level where there was a small increase in mean durations. These were striking results! They showed that the method worked. A task that was nearly impossible for children with DCD became one that they were able to perform as well as TD children who had trained at the task just as had the children with DCD. The training effectively erased the differences in performance between the groups! This result has been replicated in a number of subsequent studies in some of which the group difference was a function of age (Snapp-Childs, Fath & Bingham, 0000; Snapp-Childs et al., 2015; Snapp-Childs, Flatters, Fath, Mon-Williams, & Bingham, 2014).

3. Testing the concept behind the training

In the training regimen, support is provided to facilitate the active control of the limb movements required to accomplish the 3D tracing task. The key assumption behind the training is that the learners need to acquire better perceptuo-motor control of manual actions entailed in drawing and writing. In particular, the goal is improvement in manual compliance control where a constraint surface is perceptually detected to control movement over the surface. For improvement in active perceptually guided movement, training requires practice of such active perceptuo-motor guidance. Alternative forms of therapy employing robots have been developed to improve the production of limb movements (e.g. Kwakkel, Kollen, & Krebs, 2008; Marchal-Crespo & Reinkensmeyer, 2009). Nearly all involve using the robot to move a passive limb through a given trajectory. Such methods have been found to be relatively ineffective (Lo, Guarina, Richards, Haselkom, & Wittenberg, 2010; Reinkensmeyer & Patton, 2009). Snapp-Childs, Casserly, et al. (2013) tested active versus passive movement during training. They provided a strong test of passive movement practice by using a haptic tracking task in which participants held the stylus of the Phantom and followed it while it was driven along 3D wire paths. In this version of a passive movement, the muscles were not quiescent. Instead, they were used to maintain constant pressure of the stylus in the hand as the stylus moved. This movement was passive in the sense that learners were not required to actively guide the stylus along the 3D path, using perception to prospectively prepare for curves in the path.

Three groups of adult participants were tested. An active group trained essentially as did the participants in the previous study. A passive group followed the same paths of movement in similar time by haptically tracking the stylus while it was driven through the movements by the Phantom. A control group only performed pre- and post-training trials without actually training. As shown in Fig. 3, the passive group appeared to exhibit about half the amount of improvement as did the active group. However, the control group exhibited exactly the same amount of improvement with no training whatsoever. Necessarily, the pre-training trials were performed actively by participants in all three groups. The conclusion was that the improvement exhibited by both the passive and control groups was a result of active practice effectively provided by the pre-training trials. Improvement in performance of the task required practice of actively generated, perceptually controlled limb movements, that is, prospective control of the movements along the paths. Hence, the results supported the use of parametrically modulated support during training that requires active control of movements while making such control easier at the start of training and more difficult as skill improves. Transfer of learned skilled performance was also tested post-training with more difficult paths that were longer and more complexly curved. The finding was that only the active training group exhibited any transfer of skilled performance to these more difficult paths.

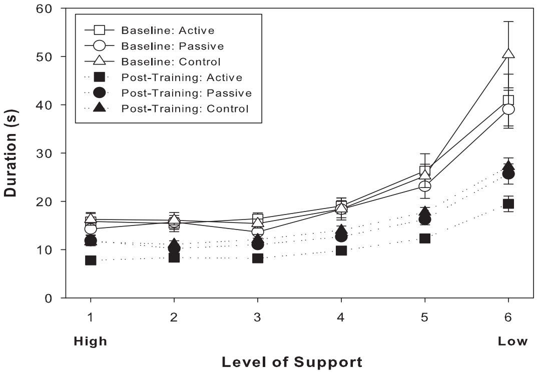

Fig. 3. Mean durations plotted as a function of level of support for the Active, Passive and Control groups both pre- and post-training. Active: squares. Passive: circles. Control: triangles. Pre-training: open symbols. Post-training: filled symbols. Error bars are standard errors (Snapp-Childs, Casserly, et al., 2013).

4. Progressive reduction of support versus constant or no support during training

The support provided in our training regimen is graduated, progressively reduced until it is essentially absent at the point that the learners have become skilled. Is this progressive reduction necessary to yield the level of performance that we have observed at the end of training? If the assumptions behind the method are correct, then the support is required to allow learning by children with DCD, in part, because learning requires practice in training and this, in turn, requires the motivation yielded by good self-efficacy. Self-efficacy during training requires a consistent good level of performance. Presumably, this requires the support that is provided in our method. Snapp-Childs, Wang, and Bingham (2016) tested three different training regimens performed by adult participants: progressive reduction, constant mid-level support, and no support. As shown in Fig. 4, all three groups exhibited the characteristic pattern of improvement in post-training trials. At post-training, the graduated support and no support groups exhibited equivalent good performance throughout, that is, at all levels of support in post-training tests, including the lowest support level. There, in contrast, the constant mid-level support group did not perform as well. They had never trained with low (or nearly no) support. Thus, they were not well prepared when they were tested with little support. An advantage of graduated support during training is that participants were prepared to bring their skill to performance without support. That is, they were ready to perform the task in normal or representative conditions in which no support is provided.

However, the results shown in Fig. 4 seem to show that the no support training group were similarly prepared and equally skilled! Is it the case, that support is not really required during training? To answer this question, performance during training was analyzed. The results of that analysis showed that the performance during training of the no support group was substantially worse than that of the other two groups. This was evident in analysis of the primary measure used in these studies, trial duration. Durations were nearly twice as long for the no support group. Why this was so was revealed by another measure used throughout these studies, namely, the number of times the stylus came off the wire path during a trial requiring the participant to locate and re-acquire the position along the path behind the ‘fish’ that was being pushed along the path. Frequency off the path was double for the no support group compared to the other two groups that trained with support. The participants in this study were TD adults. What the results showed is that we were correct in our assessment of the need for support during training for children with DCD. Enough time spent off the path and in frustration in trying to re-acquire the path to try to make progress would kill any motivation to persist in training. Children with DCD simply would not be able to do it.

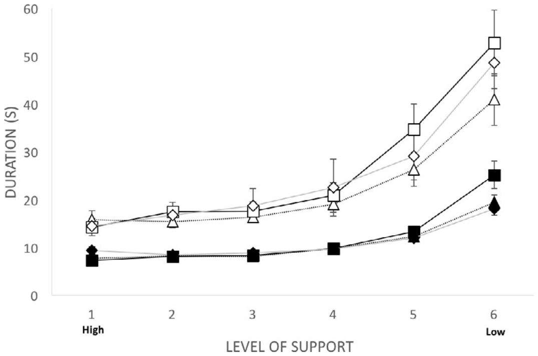

Fig. 4. Mean durations plotted as a function of level of support for the Progressively Reduced Support, Mid-Level Support and No Support groups both pre- and post-training. Progressively Reduced Support: triangles. Mid-Level Support: squares. No Support: diamonds. Pre-training: open symbols. Post-training: filled symbols. Error bars are standard errors (Snapp-Childs, Wang, et al., 2016).

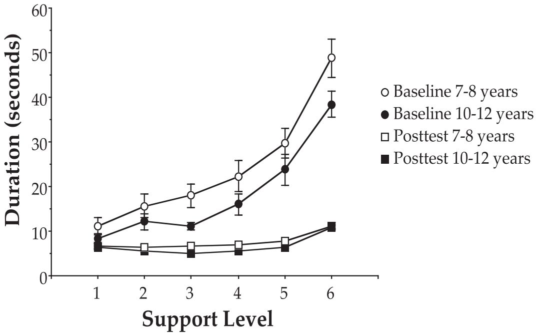

Fig. 5. Mean durations plotted as a function of level of support for the 7–8 year old and 10–12 year old groups both pre- and post- training. 7–8 year old: open symbols. 10–12 year old: filled symbols. Pre-training: circles. Post-training: squares. Error bars are standard errors (Snapp-Childs et al., 2015).

5. Where does improvement occur during training?

With the observation in this last study that participants might spend a significant amount of time off the wire path trying to reacquire it, one might wonder wherein lies improvements in times to traverse these paths. Are improvements in performance a reflection of improvements in getting back onto the path after coming off it, or instead, does improvement reflect greater speed of movement along the paths and greater success in negotiating the curves along the path so as not to come off it? The latter suggests improvement in prospective control which is the intended goal of the training. Snapp-Childs, Casserly, et al. (2013) found that the improvement in performance occurred in moving the stylus along the paths, rather than in the time to return to the path when the stylus came off it. They regressed frequency off the path on trial duration. At pre-training, the resulting relation was Duration = 2.16 × frequency off path + 12. 8. Each time participants came off the path, it took 2.16 s on average to get back onto the path. Then, it took them 12.8 s to get around the path without coming off it. The active training group at post-test yielded a change in the intercept of the relation, but not the slope: Duration = 2.16 × frequency off path + 7.6. Time to get back onto the path remained the same, but the time to go around the path dropped by nearly half to 7.6 s on average. This result was replicated by Snapp-Childs et al. (2016). Thus, the improvement was in the prospective control of the stylus as it was moved along the curved paths. The method was producing the hypothesized effects, that is, it worked as intended.

6. Testing children of different ages

Snapp-Childs et al. (2015) compared pre- and post-training performance of TD school children who were 7–8 and 10–12 years of age. The pattern of results was similar to that from the study comparing children with DCD and age matched TD children. As shown in Fig. 5, the younger children exhibited longer pre-training durations than did the older children, but at post-training children of both ages improved and age specific differences in performance were eliminated. This result was replicated by Snapp-Childs, Fath and Bingham (0000) who tested children in grades kindergarten, 2 and 3. Snapp-Childs, Shire, Hill, Mon-Williams, and Bingham (2016) tested 51 children aged 5–11 years who exhibited motor disabilities. They compared the performance of younger and older children both pre- and post-training. In contrast to the previous study, an age specific difference was not found in pre-training performance. The authors suggested that poor and variable performance yielded by motor disabilities masked any potential age differences in performance before training. However, children of all ages tested improved just as had been seen in previous studies to yield equally good performance at post-training independent of age.

7. Transfer of training in 3D tracing to 2D drawing

Our studies have shown that the approach used in our training regime yields significant improvements in compliance control of the stylus in the 3D tracing task. Transfer of this improvement in performance to 2D drawing tasks has also been investigated in a number of studies (Snapp-Childs et al., 2014; Snapp-Childs et al., 2015; Snapp-Childs, Shire, et al., 2016; Snapp-Childs et al., 0000). The transfer task is to use a stylus to copy on the screen of a tablet computer figures appearing on that screen. Different figures have been used in different studies including simple and spiral forms of circles, squares, and triangles, and then various wave forms as shown in Fig. 6. The wave forms were common to all the studies. We created software employing morphological methods to analyze the drawn copies in comparison to the target forms. Optimization methods were used to linearly transform the copies fitting them to the targets by translation, rotation, and isotropic scaling. The integrated point-to-point error distances were minimized. (See Snapp-Childs et al. (2014) for more detailed description of the analysis.) The analysis yielded both a measure of the scaling correction that was required as well as the resulting final shape error. Forms were typically drawn larger than the original targets. A finding replicated in multiple studies was that scaling errors co-varied with shape errors, that is, shape errors were larger to the extent that size errors were (e.g. Snapp-Childs et al., 2014; Snapp-Childs et al., 2015). Drawing was tested both before and after training at the 3D tracing task. The reliable finding was that shape errors significantly decreased as a result of training. Snapp-Childs, Shire, et al. (2016) used a cross over design that tested whether any improvements in drawing were specific to training. They were. They also

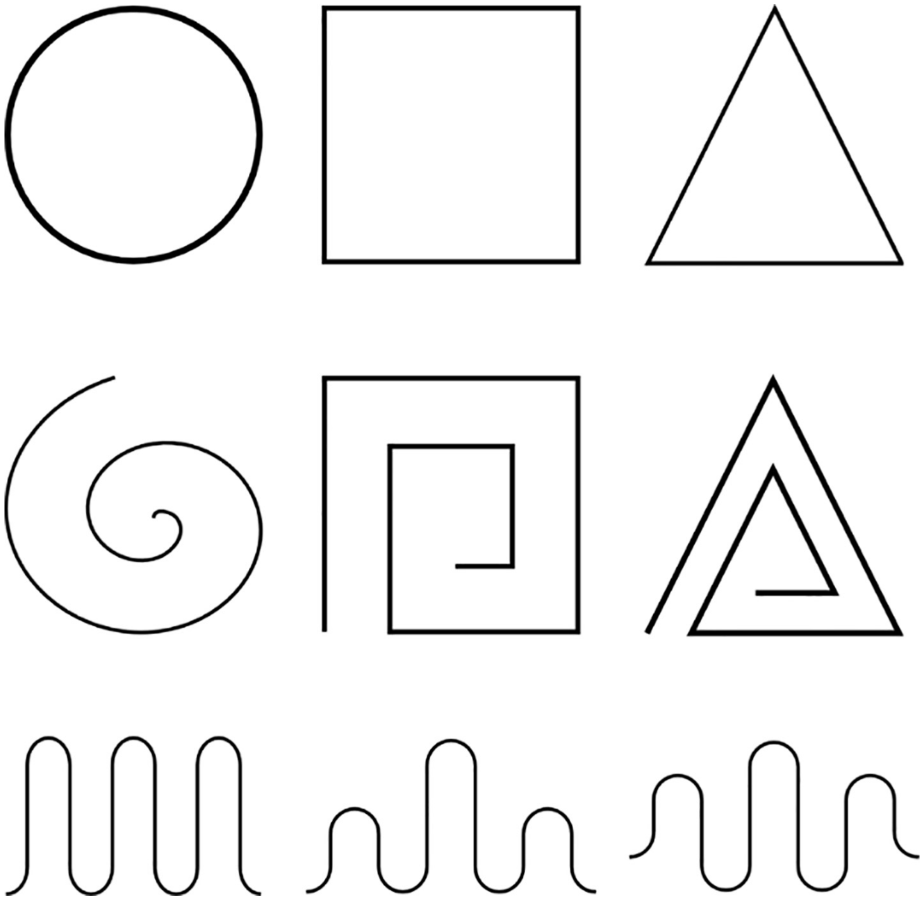

Fig. 6. Figures to be copied in the drawing task (Snapp-Childs et al., 2015).

found that younger children made larger errors before training and that as a result of training, younger children improved more with simpler figures while older children improved more with more complex figures, that is, the waves.

8. Specificity of training and transfer

In the teaching of handwriting, lined paper is typically used with lines spaced so that the children's writing is three to four times larger than it is by time they are writing in high school (Asher, 2006). A leading investigator of the teaching and learning of handwriting, Steven Graham has advocated that larger lined paper be used (Graham, Berninger, Weintraub, & Schafer, 1998; Graham, Harris, Mason, Susan, & Bruce, 2008). However, whether the production of larger letters yields better learning and performance of handwriting when learning to write remains on open question. In most of the studies in which we tested our training method for improving manual compliance control, the training path used in the 3D tracing task were not specific in two different ways to the figures used to test transfer of learning to 2D drawing. First, the paths that were traced varied in 3D whereas the paths of the figures to be copied in drawing lay in a plane. They were 2D. Among other things, this meant that the 3D paths exhibited variation in torsion as well as curvature whereas the 2D paths did not entail torsion. In this respect, the drawing task was simpler. Second, the 3D paths to be traced were larger than the 2D paths to be drawn. Snapp-Childs et al. (0000) investigated the potential role of specificity in the training in its effect on improvements in both tracing and drawing performance. First, the forms of the wire paths to be traced were made to be the same as the figures to be drawn. They were spiral and wave shapes that lay in a 2D plane. Second, the figures in both the tracing task and the drawing task were of two sizes, 3.5 cm and 7 cm, that is, one twice the size of the other. Children in three different classrooms, kindergarten, 2nd grade and 3rd grade, (and thus, of different ages) were tested and trained. In each grade, the children were assigned to one of two groups for training. One group trained with small figures and the other group trained with large figures. Both groups were tested in pre-training and post-training with both small and large figures in both tasks, tracing and drawing. The results were surprising.

We found little evidence of specificity in respect to the size of the figures. Because we were varying figure sizes systematically and thus, the lengths of the paths to be traced, it was necessary to use the path length to norm the duration measure we had previously used. Accordingly, we used a mean velocity measure. First, we found that mean velocities increased in the 3D tracing task as a result of training. (This improvement in speed had also been found in previous studies although not reported.) The increase was somewhat larger when children who had trained on large figures traced large figures. However, children who trained on small figures did not improve more when tracing small figures. More significantly, children who trained on large figures in the tracing task showed no improvement in the drawing of either large or small figures. Only the children who trained on small figures in tracing exhibited improvements in drawing and they did so equally for figures of both sizes! This was true of children in all three grades.

Thus, the results indicated that training with small figures was required to yield improvement in drawing performance. Note, however, that we did not see improvements in shape error in this study as we had in previous studies. The error remained the same. The improvement was in the speed with which the figures were drawn.

Bluteau, Coquillart, Payan, and Gentaz (2008) trained adult participants in drawing figures similar to Arabic and Japanese letters. During training, tracing of the figures on a tablet screen was performed using the stylus on a Phantom with attraction to the path of the figure similar to that used in our studies, although somewhat weaker. They did not find evidence that this improved performance evaluated in terms of the fluency or accuracy of movement. (Fluency was evaluated in terms of the mean velocity and number of velocity peaks.) The training in this study was specific to the tested writing task. However, the method was not designed specifically to improve compliance control or, relatedly, prospective control of the trajectories.

9. Relation to inventories used to diagnose DCD

Snapp-Childs, Flatters, Fath, Mon-Williams, and Bingham (2014) tested 7–8 year old school children in local schools. Before the children were tested in 3D tracing in pre-training trials, they were given the Beery VMI. The Beery inventory is frequently used to diagnose children with DCD (Cornhill & Case-Smith, 1996; Rodger, Watter, Marinac, Woodyatt, & Ziviani, 2007). Given the prevalence of DCD, children suffering from the disability might be expected in any classroom. Indeed, Snapp-Childs et al. (2014) found among the school children, children who tested at levels indicative of DCD. Subsequently, they also found that pre-training performance in the 3D tracing task co-varied with one of the three sub-section scores of the Beery[1], namely, the visual perception (VP) score. The visual perception section of the Beery tests the ability to make fine discriminations among line drawn forms. Snapp-Childs et al. suggested that this indicated that poor ability to discriminate the forms of the paths to be traced was part of the problem confronted by children with DCD. They also found that after training on the 3D tracing task, post-training performance no longer correlated with the Beery VP scores. This suggested improvement in ability to visually discriminate path shapes, and thus, improved prospective control of the movements.

10. Conclusions

We set out to develop a method for training manual compliance control to improve the ability of children to reproduce drawn figures. The method was targeted to children with DCD with the observation that these children exhibit drawing and handwriting behaviors indicative of poor compliance control. Manual compliance control entails rapid online perceptual guidance of movements that enables the actor to use a surface to simplify the generation of required trajectories. Such compliance control is a species of prospective control of limb movement that is required for good drawing and handwriting skill. The drawing of figures (including handwriting) requires additional forms of prospective control, for instance, to draw a curved line with the peak of curvature just touching a reference line. Thus, perceptual guidance that yields good prospective control of limb movement must be a signature skill for good drawing and writing ability.

Compliance control necessarily entails active generation and control of limb movements. So, improvement in compliance control wrought by training must entail practice of active generation and control of movements. The question is how to allow training with such active control to produce sufficiently reliable movements to yield progressive improvement through increased sensitivity to and use of a surface constraining the movement. An effective training method required that (1) the training task be sufficiently difficult in respect to compliance control as to leave room for significant improvement in performance and yet (2) provide a means of parametrically modifying the level of difficulty so that the task could actually be achieved by the novice performer and (3) the performance would yield improved sensitivity to and use of the constraint surface. Such modification of task difficulty would enable training that yielded consistent good self-efficacy so as to motivate the learner to train.

So, the trick was to provide support to the active generation and control of manual movement of a stylus along a constraint surface and to do so in a way that allowed support to be gradually reduced as performance improved. Gradual reduction of support was required to take the learner back to the normal un-supported task while preserving the self-efficacy yielded by good performance. The solution we devised was to make the surface magnetically attractive to the stylus so as to hold the stylus on the surface while allowing it to be moved along the surface. Using a wire as the constraint surface made the task extremely challenging while also amplifying the need to feel and see where the wire was going so as to allow the wire to guide the movement. Dragging a stylus along a magnetic wire is a task best performed with compliant control (e.g. low stiffness and force levels) to sense the wire and follow it without having to hold the stylus on the wire. The support level (that is, strength of magnetic attraction) was reduced as the learner improved in ability to follow the wire and thus, stay with the wire. This also required that the turns in the wire path be anticipated by the learner to negotiate them successfully. Thus, prospective control should improve.

The series of studies that we performed to investigate this training method showed that the method was effective in enabling children with DCD to improve so as to catch-up with TD children in respect to their performance level when performing the task after

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[1] The Beery VMI consists of 3 subsections: a visual-motor integration (VMI) section, a motor coordination (MC) section, and a visual perception (VP) section.

training without support. The method also allowed learners to perform the task successfully from the outset and thus, to maintain good self-efficacy throughout training. Parametric variation of the level of support before training both revealed children who were poor at manual compliance control (low support) and enabled them to perform as well as children who were good at compliance control (high support). Levels of performance in pre-training with low support co-varied with scores on the Beery VMI, an inventory often used to diagnose DCD. However, such co-variation was eliminated by training providing additional evidence for the success of the method. Studies revealed that improvement in performance reflected improved ability to move the stylus along the wire rapidly without coming off the wire. This supported the inference that it was perceptually guided prospective control of the movements that was improving. This was also shown by lack of improvement that was found when practice entailed robotically guided passive movement along the wire paths. We also found in multiple studies that pre-training performance in the 3D tracing task varied inversely with the age of children and that such age dependent differences were eliminated by training.

Improvement in performance yielded by the training was found to transfer to improvements in performance of a drawing task. Spatial errors in the size and shape of copied figures were reduced by the training especially for the more difficult waveform figures. Improvement in the speed of tracing and drawing was also found. The latter has been used as a measure of the fluency of the movements. These results were found in multiple studies. However, specificity of the training task to the drawing task in respect to the size, shape, and dimensionality of the paths was not required to yield good improvement, nor did it yield increased improvement. To the contrary, we found that practice of smaller scale figures yielded improvement that generalized to the drawing of figures of all shapes and sizes tested. This finding need not contradict the widely used assumption that practice in writing of large letters is to be preferred because normal writing practice in schools does not include the support to performance entailed by our method. Finally, it remains possible that the use of 3D wire paths exhibiting variations in both torsion and curvature in fact yield the best improvements in drawing performance despite the increasingly non-specific nature of the training paths in respect to shape and dimensionality. Training on such paths was found to yield both reduction of spatial errors and increases in speed of drawing. Many additional questions raised by this approach and the associated results thus far remain to be addressed. For instance, what is required for the continued maintenance of these skills remains to be determined as does the generalization to language specific writing and potential effects on reading. Nevertheless, the approach looks promising having repeatedly and reliably yielded improvements in performance that put TD and DCD children as well as children of different ages at comparable levels of skill in manual compliance control and prospective control of tracing and drawing movements.

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