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RESEARCH ARTICLE

Training children aged 5–10 years in compliance control: tracing smaller figures yields better learning not specific to the scale of drawn figures

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Abstract

Previously we developed a method that supports active movement generation to allow practice with improvement of good compliance control in tracing and drawing. We showed that the method allowed children with motor impairments to improve at a 3D tracing task to become as proficient as typically developing children and that the training improved 2D figure copying. In this study, we expanded the training protocol to include a wider variety of ages (5–10-year-olds) and we made the figures traced in training the same as in figure copying, but varied the scale of training and copying figures to assess the generality of learning. Forty-eight children were assigned to groups trained using large or small figures. All were tested before training with a tracing task and a copying task. Then, the children trained over five sessions in the tracing task with either small or large figures. Finally, the tracing and copying tasks were tested again following training. A mean speed measure was used to control for path length variations in the timed task. Performance on both tasks at both baseline and posttest varied as a function of the size of the figure and age. In addition, tracing performance also varied with the level of support. In particular, speeds were higher with more support, larger figures and older children. After training, performance improved. Speeds increased. In tracing, performance improved more for large figures traced by children who trained on large figures. In copying, however, performance only improved significantly for children who had trained on small figures and it improved equally for large and small figures. In conclusion, training by tracing smaller figures yielded better learning that was not, however, specific to the scale of drawn figures. Small figures exhibit greater mean curvature. We infer that it yielded better general improvement.

Keywords Manual control · Compliance control · Prospective control · Motor development · Specificity

Introduction

Acquiring skilled performance generally depends on practice or experience (Adolph and Robinson 2015); specifically, more practice leads to improved performance. Moreover, there is a high level of specificity with regard to practice—performance is usually best when tested under the same conditions that were present during learning. For examples, see Newell et al. (1979) and Proteau et al. (1992). At the same time, there is abundant evidence that the perception/action system is flexibly organized so that many actions can be skillfully executed despite changes in test conditions or modifications of the task. A good example of this comes from handwriting. For example, Merton (1972) showed that the shape and form of a person's signature is largely preserved across changes in the effector system used to produce the signature, an extension of the original use of handwriting by Bernstein (1967) to demonstrate motor equivalence or constancy.

More recent research, however, has shown that, despite a similar appearance, changing something as seemingly inconsequential as the scale of handwriting involves a whole host of changes. For example, changing letter size changes the mean curvature of the path (and variations in curvature) followed in writing the letter. Research in motor control of handwriting movements has revealed a reliable inverse relation between path curvature and the speed of movement at each point along the path (Lacquaniti et al. 1983). Smaller letters exhibit greater curvature and thus entail slower handwriting speed. In this respect, smaller letters are more

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difficult. Indeed, Phillips et al. (2009) demonstrated that increasing handwriting scale involved significant changes to the kinematic structure of handwriting movements: it was not a simple change in a single parameter of scale. This presents a problem for the instruction of handwriting and similar tasks—given that the kinematic structure differs between larger and smaller scale actions, must different protocols or techniques be used when teaching small versus larger scale actions? In practice, many teachers (≥ 90% in the United States) report explicit handwriting instruction (Graham et al. 2008b), and the vast majority (80%) of practice in writing by children is in tracing or copying tasks. In other respects, there was at best modest consistency in specific instructional practices used by teachers. Nevertheless, as also reported by Asher (2006), a majority of teachers use lined paper with large (0.75″–1.0″) spacing between the lines so that children learn to write by writing letters that are three or four times larger than they later characteristically write by high school as adults. A leading investigator of the teaching and learning of handwriting, Graham et al. (1998, 2008a), has advocated that such larger lined paper be used reliably. His concern was primarily with the consistency of the scale of letters when children are learning to write. Nevertheless, whether the production of larger letters yields better learning and performance of handwriting when learning to write remains an open question.

In the current study, we investigated the specificity of training and learning in the context of drawing/writing skills acquired by early school age children (grades kindergarten, 2 and 3). In our studies, we use non-alphabetic figures that resemble symbols in Australian aboriginal writing to focus on the perceptuo-motor learning aspect of this problem and avoid linguistic components or previous experience in writing given letters. We manipulated the size of figures used during training of writing skills and tested whether performance improvements were specific to the size of the figures used in training. Drawing and writing entail manual compliance control. The movement of a stylus is constrained by a 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. Compliance control is a form of prospective control, that is, online perceptual guidance and control of a trajectory that anticipates the required trajectory (Hogan 1985, 1990; Snapp-Childs et al. 2013a, b; von Hofsten 1993; Zhao and Warren 2015). Compliance control of a stylus movement along a surface allows the surface to guide and simplify the movement. Previously, we had developed a method that supports active movement generation to allow practice to yield improvement of good compliance control in tracing and drawing (Snapp-Childs et al. 2013a). We showed that the method allowed children with motor impairments to improve at a 3D tracing task to become as proficient as typically developing children and that the training improved 2D figure copying (Snapp-Childs et al. 2013b, 2014). The training method entails progressive reduction of support for tracing movements. We showed that this method was the most effective in part because it included training without support in anticipation of drawing performance under natural non-training conditions (Snapp-Childs et al. 2016a, b). Thus, the method entailed specificity of training in this respect. In the current study, we now used the method to investigate possible specificity of training effects in respect to the size of the figures traced during training. Unlike our previous studies, we now made the figures traced during training the same as the figures copied during drawing, but varied the scale of training and copying figures to assess the generality of learning. The training protocol included a range of ages (5–10-year-olds) representing the ages at which children are typically taught writing skills.

In respect to specificity, we considered two competing hypotheses. First, strict specificity of learning in respect to the size of the figures used during training would predict that the participants should exhibit greater improvement for figures of the same size experienced during training. Second, the known effects of path curvature on movement trajectories (Lacquaniti et al. 1983) would suggest that training on smaller figures might confer an advantage because smaller figures of the same form entail greater mean curvature, and thus, are more difficult. Hence, training on small figures might yield greater improvement that generalizes to both large and small figures.

Methods

Participants

A total of forty-eight children, 5–10 years old (24 female, 24 male), were recruited from the kindergarten (17 total: 7 female, 10 male; 6.17 ± 0.35 years old), the 2nd grade (16 total: 8 female, 8 male; 8.30 ± 0.32 years old), and the 3rd grade (15 total: 9 female, 6 male; 9.140 ± 0.34 years old) at a local private school. All of the children save two were right-handed. Most of the children would be considered to be typically developing; however, seven of the children were identified by their parents and their performance on a standardized assessment as having motor difficulties and probable developmental coordination disorder (DCD). Our previous studies had shown that the training method eliminated differences in performance among TD and DCD children as well as children of different ages (Winona Snapp-Childs et al. 2013a, 2014). Thus, we included all these children as participants.

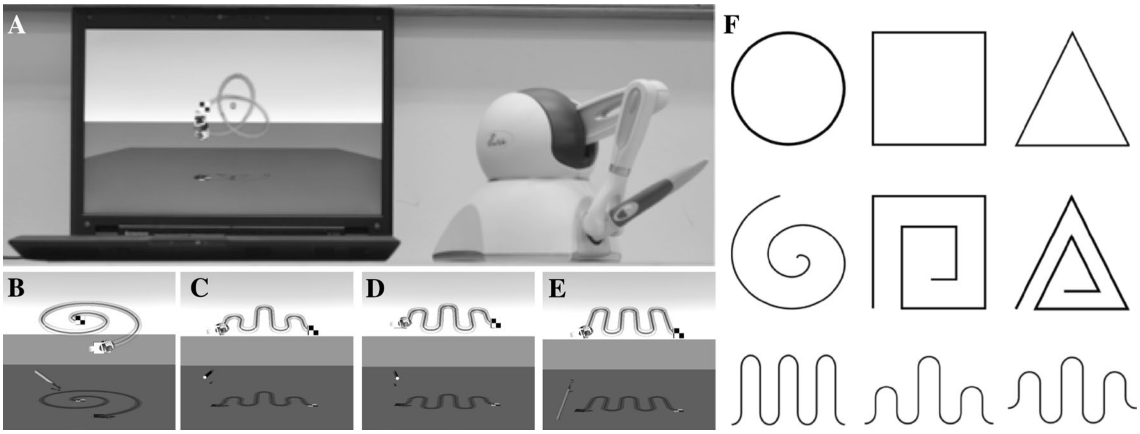

Fig. 1 **a** The PHANTOM Omni with the computer display. **b–e** The target figures for the 3D tracing task. **f** The target figures for the 2D copying task

Ethics statement

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

Procedure and apparatus

Prior to the first assessment session, the children's parents/guardians completed the Developmental Coordination Disorder Questionnaire (DCD-Q'07) (Wilson et al. 2009) at home. All assessments and training were completed at the school. The children were first assessed with the Beery–Buktenica Developmental Test of Visual–Motor Integration (Beery) and the Manual Dexterity and Balance portions of the revised Movement Assessment Battery for Children [MABC-2: (Henderson et al. 2007)]. Then participants completed a computerized 3D tracing task and 2D drawing task. Both tasks included both small and large figures. After these assessments, the participants completed a customized perceptuo-motor training program. Half of the children in each grade were randomly assigned to the large figure training group, while the other half were assigned to the small figure training group. After training, participants were again assessed at the 3D tracing and 2D drawing tasks.

3D tracing

The 3D tracing task was similar to that used in previous studies except the 3D wire paths to be traced were planar figures similar to the figures in the copying task. These involved only variations in curvature. In previous studies, the paths were more like roller coaster paths with both curvature and torsion. In this study, participants sat at a table to perform the tracing task. The basic task was to view a curved path in a computer graphics display and use a stylus to push a brightly colored fish along the path from a small plain square, marking the starting location, to a checkered square, marking the finishing location, 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; see Fig. 1a) and used the stylus to feel the wire path and push the fish along it. The stylus could be seen in the computer graphics display moving just as did the stylus held and moved in the hand.

The PHANTOM is an impedance control device that allows a user to move a 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 have been minimized by careful mechanical design. In this experiment, participants could "feel" the 3D path once they encountered it. The 3D tracing task was made easier or more difficult by a parametrically varied force that held the stylus on the wire path. Greater force made the task easier. This encouraged improved compliance control because the optimal way to perform the task with this attractive force was to feel the wire haptically and simply move the stylus along it without having to work to keep the stylus in contact with the wire. Phenomenologically, it was as if the stylus was "magnetically attracted" to the path. This attractive force pulling the stylus towards the wire path was modeled as a virtual spring with variable stiffness. The spring had a virtual length of approximately 0.5 cm from the center of the path so the force dropped to zero if the stylus moved to a distance greater than 0.5 cm from the path. The spring stiffness (and consequently the level of "attraction" or support) was parametrically varied to alter task difficulty. See Snapp-Childs et al. (2013a, 2016a, b) for additional explanation.

At baseline and post-training, participants attempted small (3.5 cm) and large (7 cm) versions of four shapes (one spiral, three wave forms) at three levels of support (attractive forces of 2.02, 0.70, and 0.13 N; that is, high, medium, and low support), resulting in a total of 24 trials (Fig. 1b–e). All were practiced in each session in a different random order. The first wave was of constant amplitude. In the second, 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 third was similar to the second but the small amplitude cycles were centered vertically, i.e., both the tops and bottoms of each cycle varied. These were 2D shapes, but were slanted at an angle of 27° from horizontal, so movement along these paths was in three dimensions. The suspended 3D wire path aspect was retained as essential to feature the need for good compliance control. The competitor fish took 20 s to travel the path from start to finish. The children were instructed to complete the path as quickly as they could with the goal of 'beating' the competitor fish.[1]

3D tracing training

The training program consisted of five 20-min training sessions that were separated from one another by 1 week. The children performed training in a room outside of the classroom and did so in groups of four to six, each child working at his or her own workstation. During the training sessions, participants performed a series of 3D tracing tasks that were similar to those in the baseline/post-training sessions, except half of the children only trained with the small versions of the shapes (small training group) and the other half trained with the large shapes (large training group). During training, participants raced against two different competitors: one competitor completed the path in 20 s while the other completed the path in 10 s. The first training session started with the highest level of support (attractive force) and slowest competitor. The goal of the training was to allow the children to progress at their own pace through the different combinations of levels of attraction, paths, and competitors. We used a "two-wins-in-a-row" rule to determine when the children progressed. After the participant "beat" the slowest competitor two times-in-a-row they progressed to the faster competitor.[2] Once the participant beat both competitors they then moved to the next shape with the slowest competitor. After all paths and competitors were "beaten", the level of support was decreased and the participant re-started with the first shape and slowest competitor. Six levels of support were used during training (2.02, 1.08, 0.83, 0.57, 0.35 and 0.13 N). Note: The medium level of the three support levels used in assessment sessions was 0.70 because this was the mean of the third (0.57) and fourth (0.83) levels of support in training.

2D drawing

In the drawing test, participants were seated at a table in front of a tablet PC (Toshiba Portégé M750 with screen size 163 × 260 mm or Samsung ATIV Smart PC Pro 700T with screen size 145 × 257 mm). The tablets used customized software to manage stimulus presentation, user interface, and data collection as described by Culmer et al. (2009). The task was to view a form at the top of the screen and then copy the form at the bottom of the screen using a handheld stylus in the dominant hand.

All stimuli were set against a white background. When a trial started, 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 form inside the black frame and then placed the handheld stylus on the green rectangle at the location where they would start copying the form. Once the stylus was inside the green 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—similar to the black frame in the upper portion of the screen containing the form to be copied. Once participants began to draw the form, an "OK" button appeared in the upper right-hand corner of the screen. Participants were instructed to copy the figures accurately in respect to size and shape. When participants finished copying the form, they tapped this button with the stylus, completing the current trial and beginning the next one. To become familiar with the task and interface, participants performed three practice trials (a horizontal line segment, one cycle of a sine wave, and a circle) that were not analyzed. Then, participants completed two repetitions of both large and small versions of the four forms used in the 3D tracing task in a random order (see Fig. 1f for a depiction of the large versions); this resulted in a total of 30 figures that were copied.

Data analysis

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 with the

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[1] In previous studies, children would take a long time when completing trials with low attractive force, which would cause frustration. To mitigate this, each trial was terminated if a child could not complete more than one-half of the path within 60 s.

[2] If a child did not beat the competitor fish twice in a row within 6 trials, s/he would automatically advance to the next stage of training.

known coordinates of the target trajectory (the path), we computed both temporal and spatial–temporal measures of performance. Trial duration was computed as a temporal measure. 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). In previous studies, we had 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. However, in the current study, the target paths were varied systematically in respect to size and, therefore, path length. Thus, to provide an appropriate measure for comparison of performance between the two sizes and changes thereof, we computed a mean speed for each trial by dividing the trial duration into the path length of the target figure. An important variable in the analysis of manual movements along a target path is the path curvature, given the well-established functional relation in such movements between the path curvature and the speed of movement along the path, speed of movement was expected to vary with target size. Smaller targets of the same figure would exhibit greater mean curvature and thus, the mean speed would be expected to be smaller. The mean speed was a doubly appropriate measure of performance. Nevertheless, we initially analyzed the trial durations to determine whether we had replicated results in our previous studies in which we had investigated this training method with children of different ages. In this analysis, we collapsed over the size variations and training groups to investigate only the effects of session, support, and grade as in our previous studies. All five factors were included in the remaining analyses. Finally, we also computed the frequency off the path, that is, the number of times during each trial that the stylus came off of the path. Each such occurrence would cost the participant extra time to return to the path at the point where the stylus left it, thus increases total trial duration. We included figure size and training group in this analysis in addition to the other three factors.

We averaged the dependent measures separately for each participant, over the trials performed in a given condition (level of support and figure size) and session (baseline and post-training).

2D 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 main variables for each of the forms that participants produced: shape error and mean speed. Duration was simply the length of time that it took the participants to draw each figure. To control for the different sizes of the target figures to be drawn, we computed a mean speed for each trial, just as was done with the 3D figures. We divided duration into the target path length. To find shape error, 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 (Myronenko and Song 2010) to determine the transformation that makes the participant-generated path most closely match the reference path. Productions were rotated and scaled isotropically to minimize resulting error. 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. Lower values represent better shape accuracy and, therefore, less error. See Snapp-Childs et al. (2014) for additional explanation. ANOVAs were performed with four factors: figure size, training group, session, and grade.

Results

3D tracing

Duration

In our previous studies, trial duration was used as a measure of performance in the 3D tracing task. We now performed an analysis on durations comparing grades, sessions and support levels to determine whether results of our previous studies were replicated. As shown in Fig. 2, mean durations varied with the level of support in baseline. As previously found, durations were increasingly long with decreasing levels of support. Durations were longer for younger children and more so with lower amounts of support. As also shown in Fig. 2, durations decreased with training so that at posttest, age differences were eliminated. Only a small variation in duration as a function of level of support remained. These results replicated those of previous work (Snapp-Childs et al. 2016a, b).

We performed a mixed-design ANOVA on durations with grade (kindergarten, 2nd grade, 3rd grade) as a between-subject factor and session (baseline, posttest) and support (high, medium, low) as repeated measures factors. The ANOVA yielded main effects for grade [$F(2, 45) = 10.8$, $p < 0.001$; $\eta^2 = 0.10$], session [$F(1, 45) = 56.0$, $p < 0.001$; $\eta^2 = 0.21$], and support [$F(2, 90) = 139.0$, $p < 0.001$; $\eta^2 = 0.49$]. There were also significant interactions of grade by support [$F(2, 45) = 4.8$, $p < 0.05$;

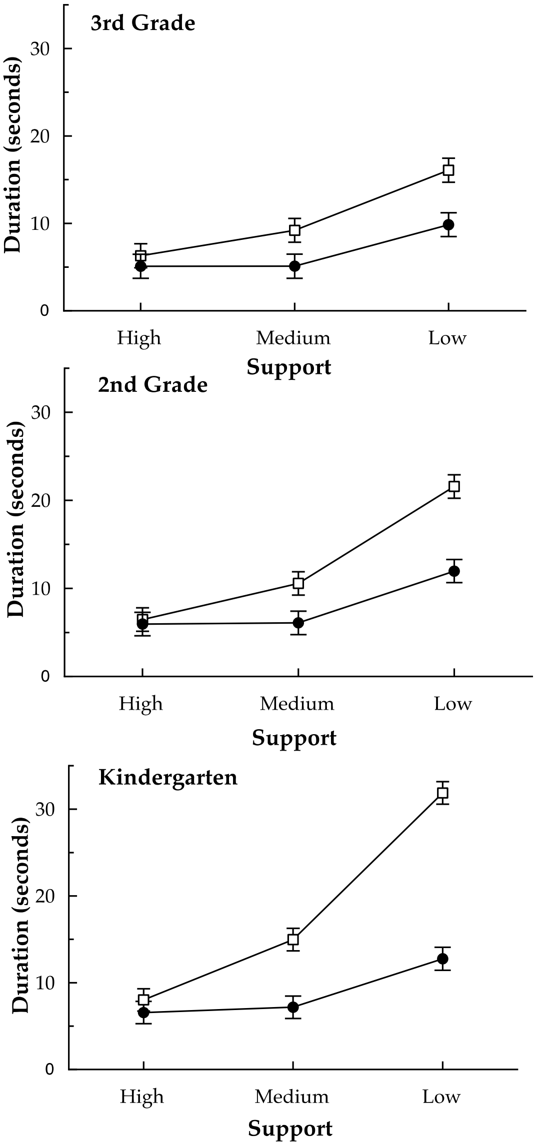

Fig. 2 Mean trial durations in the 3D tracing task plotted separately for each grade as a function of the three support levels and two sessions. Baseline: open squares. Posttest: filled squares. Error bars are standard errors

$\eta^2 = 0.02$], grade by session [$F(4, 90) = 5.6$, $p < 0.001$; $\eta^2 = 0.04$], session by support [$F(2, 90) = 24.6$, $p < 0.001$; $\eta^2 = 0.11$], and grade by session by support [$F(4, 90) = 3.48$, $p < 0.05$; $\eta^2 = 0.03$]. Given these significant interactions, we performed separate ANOVAs on the durations for each session. At baseline, there were main effects of grade [$F(2, 45) = 9.0$, $p < 0.001$; $\eta^2 = 0.09$] and support [$F(2, 90) = 82.9$, $p < 0.001$; $\eta^2 = 0.40$] as well as a grade by support interaction [$F(4, 90) = 5.4$, $p < 0.001$; $\eta^2 = 0.05$]. At posttest, there was only a main effect of support [$F(2, 90) = 45.7$, $p < 0.001$; $\eta^2 = 0.34$].

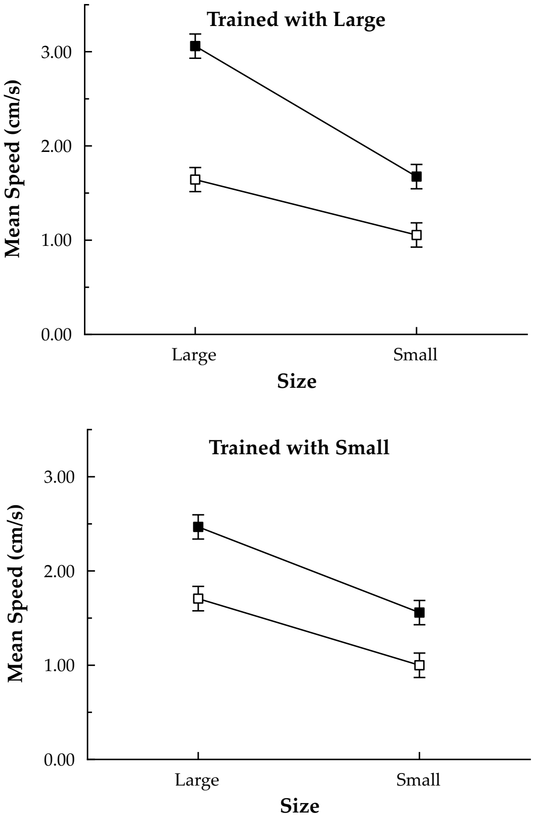

Fig. 3 Mean speeds in the 3D tracing task plotted separately for each training group (large and small) as a function of the two figure sizes and two sessions. Baseline: open squares. Posttest: filled squares. Error bars are standard errors

Speed

To reduce the complexity of analyses, we analyzed performance with the lowest support level (low support) to evaluate the specificity of training in respect to the size of the figures. The low support level is most relevant to performance in normal drawing and writing tasks. As shown in Fig. 3 (and in Table 1), we found that training increased the mean speed both for small and large figures irrespective of the size of the figures traced during training. We were investigating whether the size of figures experienced during training would differentially improve subsequent performance with same-sized figures both in the 3D tracing task used for training and in the 2D drawing transfer task. Now, in the 3D tracing task, we found that children who trained with large figures improved more when tracing large figures in posttest. However, a similar specificity effect was not found for children who trained on small figures.

We performed a mixed-design ANOVA on mean speeds with grade (kindergarten, 2nd grade, 3rd grade) and training group (small figure trained vs. large figure trained) as between-subject factors and session (baseline, posttest),

Table 1 Summary data for the speed of 3D tracing tasks

Session	Grade	Figure size	Training group	Level of support	Speed (cm/s) (SE)	
Baseline	Kindergarten	Large	Large	High	3.51	0.20
				Medium	2.45	0.23
				Low	1.29	0.18
			Small	High	3.70	0.23
				Medium	2.53	0.21
				Low	1.15	0.11
		Small	Large	High	2.09	0.16
				Medium	1.67	0.16
				Low	0.64	0.08
			Small	High	2.29	0.16
				Medium	1.68	0.18
				Low	1.09	0.06
	Second	Large	Large	High	4.16	0.26
				Medium	3.48	0.26
				Low	1.79	0.19
			Small	High	3.93	0.27
				Medium	3.51	0.26
				Low	1.80	0.21
		Small	Large	High	3.10	0.18
				Medium	2.01	0.23
				Low	1.19	0.14
			Small	High	2.69	0.19
				Medium	2.23	0.21
				Low	1.09	0.10
	Third	Large	Large	High	4.46	0.33
				Medium	3.75	0.30
				Low	1.84	0.16
			Small	High	4.62	0.24
				Medium	3.68	0.36
				Low	2.17	0.19
		Small	Large	High	3.26	0.29
				Medium	2.12	0.19
				Low	1.30	0.10
			Small	High	2.75	0.21
				Medium	2.35	0.27
				Low	1.30	0.12

Table 1 (continued)

Session	Grade	Figure size	Training group	Level of support	Speed (cm/s) (SE)	
Posttest	Kindergarten	Large	Large	High	3.46	0.14
				Medium	4.36	0.22
				Low	2.85	0.22
			Small	High	3.53	0.20
				Medium	3.66	0.29
				Low	2.22	0.16
		Small	Large	High	2.43	0.11
				Medium	2.46	0.13
				Low	1.57	0.12
			Small	High	3.00	0.12
				Medium	2.45	0.17
				Low	1.53	0.13
	Second	Large	Large	High	4.90	0.31
				Medium	4.53	0.34
				Low	2.58	0.21
			Small	High	3.69	0.28
				Medium	4.52	0.20
				Low	2.75	0.13
		Small	Large	High	3.08	0.16
				Medium	2.38	0.19
				Low	1.41	0.12
			Small	High	2.78	0.22
				Medium	2.99	0.18
				Low	1.56	0.13
	Third	Large	Large	High	5.12	0.23
				Medium	6.11	0.31
				Low	3.78	0.25
			Small	High	4.45	0.24
				Medium	4.67	0.28
				Low	2.44	0.16
		Small	Large	High	3.30	0.13
				Medium	3.07	0.19
				Low	2.12	0.19
			Small	High	3.30	0.20
				Medium	2.88	0.19
				Low	1.59	0.11

figure size (small vs. large) and figure shape (spiral, waves 1–3) as repeated measures factors. The ANOVA yielded main effects of grade [$F(2, 42) = 8.3$, $p < 0.01$; $\eta^2 = 0.12$], session [$F(1, 42) = 69.9$, $p < 0.001$; $\eta^2 = 0.36$], and size [$F(1, 42) = 215.1$, $p < 0.001$; $\eta^2 = 0.38$]. There were also significant interactions of session by size [$F(1, 42) = 18.5$, $p < 0.001$; $\eta^2 = 0.03$], session by figure shape [$F(1, 124) = 2.7$, $p < 0.05$; $\eta^2 = 0.01$], and group by session by size [$F(1, 42) = 6.8$, $p < 0.05$; $\eta^2 = 0.01$]. Older children were faster overall. Speeds increased with training. Mean speeds were greater for large figures as was expected because the mean curvature is lower than for small figures. The two- and three-way interactions with session reflected the differential increase in speed for children that trained with large figures when they traced large figures in posttest. The large constant amplitude wave was faster than other figures.

Frequency off path

As shown in Fig. 4, the frequency off path decreased with training. For kindergarten children, the decrease was the same for small and large figures, but for the 2nd and 3rd grade children, the decrease was considerably greater for

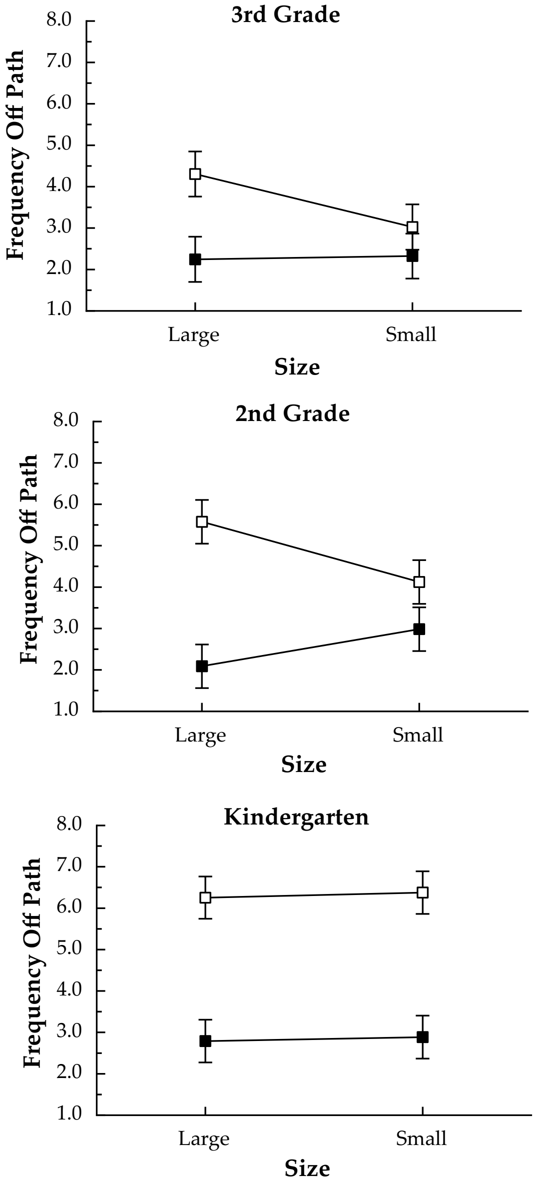

Fig. 4 Mean frequency off path in the 3D tracing task plotted separately for each grade as a function of the two figure sizes and two sessions. Baseline: open squares. Posttest: filled squares. Error bars are standard errors

large figures than small ones so that the frequency was actually lower for large figures at posttest.

We analyzed frequency off path only at the lowest level of support (low support). We performed a mixed-design ANOVA on frequency off path with grade (kindergarten, 2nd grade, 3rd grade) and training group (small figure trained vs. large figure trained) as between-subject factors and session (baseline, posttest), figure size (small vs. large) and figure shape (spiral, waves 1–3) as repeated measures factors. The ANOVA yielded main effects of grade [$F(2, 42) = 6.0$, $p < 0.01$], session [$F(1, 42) = 34.8$, $p < 0.001$], and shape [$F(3, 124) = 18.4$, $p < 0.001$]. There were also significant interactions of session by size [$F(1, 42) = 12.0$, $p < 0.005$], and grade by session by size [$F(2, 42) = 4.0$, $p < 0.05$]. Mean frequency was lower for older children, greater for spirals and the first wave than for the last two waves, and lower at posttest than at baseline.

2D drawing (copying)

Speed

The question was whether the training in the 3D tracing would transfer to a 2D drawing task in a way that was specific to the training in respect to the size of the figures traced and drawn. The shapes of the figures were the same in the two tasks (although a couple of additional spiral shapes also were tested in drawing). Also, the large and small sizes of the figures were the same in the two tasks. We analyzed the same measure (e.g., mean speed) for drawing as for tracing for the same reason, that is, to encompass both the trial duration goal for performance and the path length variations entailed by the large and small sizes. As shown in Fig. 5 (and in Table 2), the finding was that improvements in drawing performance at posttest did not reflect specificity to figure size in training. However, only training with small size figures yielded significant improvement in performance.

We performed a mixed-design ANOVA on mean speeds with grade (kindergarten, 2nd grade, 3rd grade) and training group (small figure trained vs. large figure trained) as between-subject factors and session (baseline, posttest), figure size (small vs. large) and figure shape (spiral vs. wave) as repeated measures factors. The ANOVA yielded main effects of grade [$F(2, 42) = 10.3$, $p < 0.001$; $\eta^2 = 0.09$], session [$F(1, 42) = 8.8$, $p < 0.005$; $\eta^2 = 0.01$], shape [$F(1, 42) = 62.4$, $p < 0.001$; $\eta^2 = 0.04$], and size [$F(1, 42) = 936.7$, $p < 0.001$; $\eta^2 = 0.81$]. There were also significant interactions of session by size [$F(1, 42) = 4.9$, $p < 0.051$; $\eta^2 = 0.002$], grade by size [$F(1, 42) = 4.12$, $p < 0.05$; $\eta^2 = 0.007$] and grade by group by session by shape [$F(1, 42) = 4.7$, $p < 0.05$; $\eta^2 = 0.003$]. Given this last interaction, we performed separate ANOVAs on the mean speed data for each training group. The ANOVA on trained large data yielded main effects for grade [$F(2, 21) = 4.7$, $p < 0.05$; $\eta^2 = 0.09$], shape [$F(1, 21) = 23.0$, $p < 0.001$; $\eta^2 = 0.03$], and size [$F(1, 21) = 405.0$, $p < 0.001$; $\eta^2 = 0.85$] as well as a significant grade by session by shape interaction [$F(2, 21) = 5.2$, $p < 0.05$; $\eta^2 = 0.008$]. The ANOVA on trained small data yielded main effects for grade [$F(2, 21) = 5.87$, $p < 0.01$; $\eta^2 = 0.09$], session [$F(1, 21) = 9.4$, $p < 0.01$; $\eta^2 = 0.03$], shape [$F(1, 21) = 39.4$, $p < 0.001$; $\eta^2 = 0.06$], and size [$F(1, 21) = 549.4$, $p < 0.001$; $\eta^2 = 0.78$]. None of the interactions reached significance. Mean speeds were larger for older children before and after training in both groups. Speeds increased with training only for children

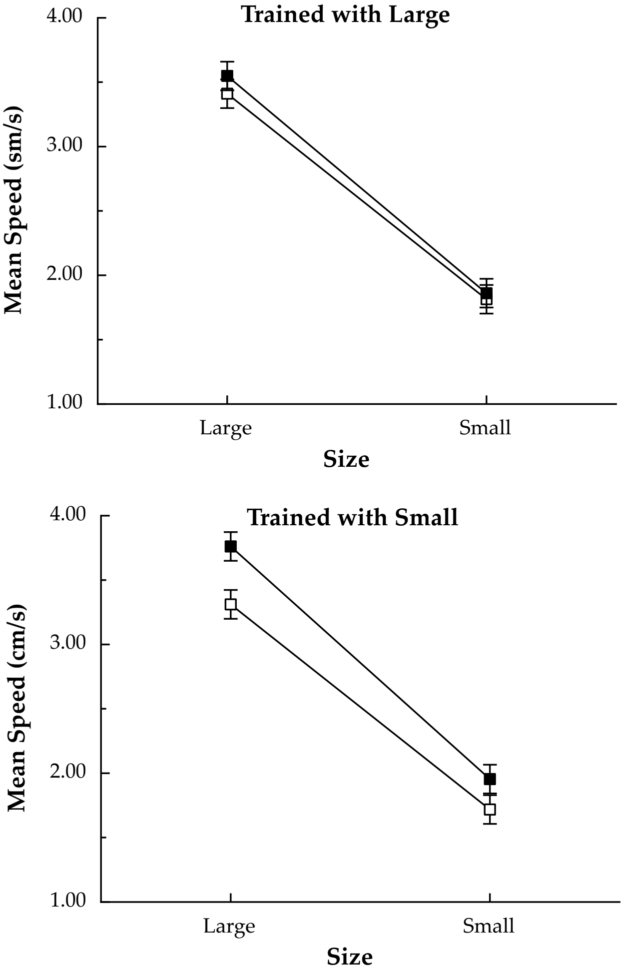

Fig. 5 Mean speeds in the 2D copying task plotted separately for each training group (large, small) as a function of the two figure sizes and two sessions. Baseline: open squares. Posttest: filled squares. Error bars are standard errors

who trained with small figures. Mean speeds were greater for spirals than for waves and for large figures than for small ones.

Shape error

Improvement in speed was the explicit goal of the 3D training task. We found corresponding improvements in the speed of 2D drawing. Increased speed, however, can yield greater spatial errors. However, we found no change in spatial errors as a result of training.

We performed a mixed-design ANOVA on spatial errors with grade (kindergarten, 2nd grade, 3rd grade) and training group (small figure trained vs. large figure trained) as between-subject factors and session (baseline, posttest), figure size (small vs. large) and figure shape (spiral vs. wave) as repeated measures factors. The ANOVA yielded main effects of grade [$F(2, 42) = 13.9$, $p < 0.001$; $\eta^2 = 0.22$], shape [$F(1, 42) = 47.7$, $p < 0.001$; $\eta^2 = 0.25$], and size [$F(1, 42) = 97.7$, $p < 0.001$; $\eta^2 = 0.25$]. Session was not significant ($p > 0.7$). There were significant interactions of grade by shape [$F(2, 42) = 3.7$, $p < 0.05$; $\eta^2 = 0.04$], grade by size [$F(2, 42) = 4.0$, $p < 0.05$; $\eta^2 = 0.02$], shape by size [$F(1, 42) = 29.8$, $p < 0.001$; $\eta^2 = 0.07$], and grade by shape by size [$F(2, 42) = 8.9$, $p < 0.05$; $\eta^2 = 0.04$]. Errors were smaller for older children. They were larger for waves than for spirals. They were larger for larger figures. The difference among ages was larger for waves and for large figures and the difference between spirals and waves was larger for larger sized figures and more so for younger children.

Discussion

The purpose of this study was to examine potential specificity of training in compliance control using a 3D tracing task and the transfer of this training to a 2D copying task. The figures traced and copied, respectively, were the same in respect to shape and size (two additional figures, square and triangular spirals, were also tested in 2D copying.). In particular, small (≈ 3.5 cm tall) and large (≈ 7 cm tall) figures were tested in both tasks in baseline and posttest sessions. During multiple training sessions, members of two groups in each of the three grades practiced the 3D tracing task experiencing only small or large figures, respectively. Thus, if skills entailed in drawing of these figures are size specific, we should expect that children who had practiced with small figures should perform in posttest better with small figures in both the 3D tracing and the 2D copying (and vice versa for children who had practiced with large figures). Furthermore, the speed of the competitor fish was greater during training with larger figures. In this respect, training specificity should yield high speeds for this group for both small and large test figures and thus, we should have seen a main effect of the training group factor in ANOVAs. However, this is not what we found.

Instead, we found different results in the 3D tracing task and in the 2D copying task. In the 3D tracing task, we found that children who trained with the large figures improved more when tracing the large figures than the small ones. With improvement, mean speeds increased. There was equal improvement for tracing of large and small figures by children who had trained with small figures, that is, there was no differential improvement. On the other hand, in the 2D copying task, only children who had trained with small figures exhibited improvement and equally so for both small and large figures. Children who had trained with large figures failed to exhibit improvement in 2D copying.

We also recorded the frequency of coming off the path during each trial of the 3D tracing task. We found that

Table 2 Summary data for performance in the 2D drawing tasks

Session	Grade	Figure size	Training group	Figure shape	Speed (SE)	
Baseline	Kindergarten	Large	Large	Spiral	3.28	0.15
				Wave	2.61	0.15
			Small	Spiral	3.25	0.15
				Wave	2.73	0.13
		Small	Large	Spiral	1.9	0.13
				Wave	1.38	0.07
			Small	Spiral	1.69	0.07
				Wave	1.31	0.07
	Second	Large	Large	Spiral	3.47	0.2
				Wave	3.18	0.16
			Small	Spiral	3.59	0.13
				Wave	2.91	0.13
		Small	Large	Spiral	2.01	0.08
				Wave	1.54	0.07
			Small	Spiral	1.92	0.07
				Wave	1.53	0.06
	Third	Large	Large	Spiral	3.75	0.14
				Wave	3.71	0.16
			Small	Spiral	3.8	0.14
				Wave	3.34	0.11
		Small	Large	Spiral	2.09	0.07
				Wave	1.94	0.08
			Small	Spiral	2.08	0.06
				Wave	1.75	0.07
Posttest	Kindergarten	Large	Large	Spiral	3.19	0.14
				Wave	2.76	0.14
			Small	Spiral	3.71	0.18
				Wave	3.03	0.2
		Small	Large	Spiral	1.81	0.08
				Wave	1.32	0.07
			Small	Spiral	1.93	0.1
				Wave	1.5	0.07
	Second	Large	Large	Spiral	3.6	0.15
				Wave	3.45	0.13
			Small	Spiral	3.79	0.17
				Wave	2.92	0.12
		Small	Large	Spiral	1.97	0.08
				Wave	1.61	0.06
			Small	Spiral	2.2	0.1
				Wave	1.46	0.06
	Third	Large	Large	Spiral	4.34	0.16
				Wave	3.7	0.2
			Small	Spiral	4.69	0.17
				Wave	3.91	0.15
		Small	Large	Spiral	2.42	0.09
				Wave	1.99	0.09
			Small	Spiral	2.55	0.09
				Wave	2.14	0.11

these frequencies decreased after training. However, they decreased much more for large target figures than for small ones so that, after training, frequencies for large figures were less than for small figures, whereas before training, frequency was less for small figures. The implication of this last result is that mean speeds increased in the performance of large figures after training mostly because participants were no longer coming off the paths and having to spend time reacquiring the paths. This result also implies that the significant improvements in performance of small figures simply reflected greater speed of tracing along the small paths rather than a large change in frequency of coming off the paths. This seems to have translated into improved performance of the 2D copying task by participants who trained with small figures. In addition, the small figures entailed greater variations in curvature (reflected in greater mean curvatures) because the straight sections of the wave figures continued to exhibit zero curvature (by definition) while the curves in the smaller waves exhibited much larger curvature. Presumably, training with this increased difficulty in the tracing task yielded better performance in the copying task. We showed in previous studies that the training improved prospective control, meaning in part that the curves in the path were anticipated in the manual control of the stylus trajectory (Snapp-Childs et al. 2013a). Training with curves of greater curvature would increase demand for such prospective control.

Finally, we also found that the results of the current study replicated those of previous studies in respect to effects of age differences. Younger children exhibited much larger trial durations at baseline with low levels of support. High support levels yielded equivalent performance by children of different ages even at baseline. This effect was used in training protocols to yield high self-efficacy so that the children would (and do) enjoy the training. With training, trial durations decreased especially at low support levels. Training eliminated differences in mean trial durations among different aged children with the exception of some small residual differences at the lowest support level. These results were replicated. However, we did not replicate previous findings of reduced spatial errors in 2D drawing. We did now find improvement in drawing performance in respect to the mean speeds of copying. This had also occurred in previous studies although we had not reported it having focused instead on reduction of spatial errors. Why did we not see changes in spatial errors in the current study? The training figures in the 3D tracing task were different in the current study compared with past studies. In this study, the figures were designed to be similar to those in the drawing task both in shape and size. The shapes meant that the paths each lay in a plane. Such paths exhibit curvature, but no torsion. 3D training paths in previous studies were fully 3D, that is, roller coaster-like paths that entail variations in torsion as well as curvature. It is possible that such paths yield better training of compliance control that better applies to control of spatial error in subsequent drawing tasks.

Implications for handwriting instruction

A debate has occurred in the United States about whether or not to teach schoolchildren handwriting (e.g., see Mandelstam 2015). In the past, teachers have done so (Graham et al. 2008a) but in many states the requirements to teach handwriting were removed although many have more recently reinstated such requirements. Notably, the national Common Core (Common Core State Standards Initiative 2009) does not include (cursive) handwriting instruction. Nonetheless, teachers to a large extent are actively engaged in handwriting instruction (Graham and Harris 2009). Graham et al. (2008a), for instance, identified a number of specific instructional procedures that teachers used to teach letter formation to primary school children. The most commonly used procedures were modeling letter formation (97% of teachers), praising students (86%), having students trace (80%) and copy (79%) letters, identifying correctly and incorrectly formed letters (69 and 66%, respectively), and cues to show letter formation (61%).

However, what was notably missing was a description of activities such as drawing that involve similar movements but dissimilar cognitive components. We believe that this oversight might be problematic particularly for struggling writers. The body of research from Graham (1990) and Weintraub and Graham (1998) indicates that poor writers and children with learning disabilities struggled to produce letters in addition to routinely misspelling words and ignoring or misplacing capitalization and punctuation. Graham speculated that the slow production was a likely cause of the mistakes (spelling, capitalization, punctuation, etc.) (Graham and Harris 2009). What we have described in this work is a method for improving the production skills; in this case, tracing smaller shapes led to improved production skills.

From a neurocognitive perspective, writing practice is fairly well established to facilitate neural specialization for letters (James et al. 2005; Vinci-Booher and James 2016). Moreover, there is good evidence that active training facilitates letter perception but passive observation does not (Kersey and James 2013). Specifically, Kersey and James showed that perceptual networks for newly learned cursive letters are driven by motor execution (Kersey and James 2013) [The findings of Kersey and James are consistent with our previous work showing that passive learning is inferior to active learning (Snapp-Childs et al. 2013a, b)]. However, it is entirely unclear if there would be any identifiable neural mechanism that would account for the differences that we found for training with smaller vs. larger figures. We predict that the brain activation patterns and associated recruitment networks would be similar between the two training conditions; however, future research will be needed to investigate this issue.

Conclusions

The results from this study are in line with our previous work; haptic training improves manual production skills in primary school-aged children. However, relatively small figures used during training are more beneficial.

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