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Children's ability to learn a motor skill is related to handwriting and reading proficiency

Mona S. Julius [a], Rivka Meir [a], Zivit Shechter-Nissim [a], Esther Adi-Japha [a,b,*]

[a] School of Education, Bar-Ilan University, Ramat-Gan, Israel
[b] Gonda (Goldschmied) Multidisciplinary Brain Research Center, Bar-Ilan University, Ramat-Gan, Israel

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ABSTRACT

The current study, conducted over two years, hypothesizes a direct link between procedural learning of motor-tasks and language-related skills, such as handwriting and reading. Fifty-six children, aged 5- to 8-years, who practiced a simple grapho-motor task, improved their performance during training. Additional, consolidation ('offline'), gains were shown 24 h post-practice and retained two-weeks later. Accuracy was maintained, as previously reported (Julius & Adi-Japha, 2015). In Phase I of the study reported here, handwriting (speed and legibility) was assessed contemporaneously with the motor-task. In Phase II, conducted the following year, handwriting and reading-speed were assessed. Averaged performance-accuracy of the motor task was associated with contemporaneous handwriting-legibility, beyond age and socioeconomic status. Performance-speed assessed 24 h post-practice was associated with contemporaneous handwriting-speed, and with following-year handwriting- and reading-speed, beyond age, socioeconomic status, and initial performance-speed, underscoring learning. The association between task-performance-speed and following-year handwriting-speed was mediated by following-year reading-speed, emphasizing individual differences in procedural learning across different domains.

1. Introduction

Procedural memory is integral to the learning of cognitive, perceptual, motor, and linguistic skills (Ullman, 2004; Vicari et al., 2005) that contribute to school achievements. Procedural learning is a basic mechanism enabling newly acquired skills to improve gradually across multiple learning experiences (Censor, Sagi, & Cohen, 2012). Laboratory-based evidence indicates that the learning of nonlinguistic and linguistic skills share this basic mechanism (Bitan & Booth, 2012; Dayan & Cohen, 2011; Karni et al., 2005). For example, gradual improvement was exhibited by children and adults who learned a motor task (Bosga-Stork, Bosga, & Meulenbroek, 2014; Dorfberger, Adi-Japha, & Karni, 2007, 2009, 2012; Savion-Lemieux, Bailey, & Penhune, 2009), a linguistic task (Ferman & Karni, 2010; Morgan-Short, Sanz, Steinhauer, & Ullman, 2010), wrote non-words (Dorfberger et al., 2009), or learned to read a novel orthography (Bitan & Booth, 2012). The current study examines the link between how kindergarteners and second-grade students learn a laboratory, letter-like, grapho-motor task (Julius & Adi-Japha, 2015), and their performance in handwriting and reading, assessed contemporaneously (Phase I) and a year later (Phase II).

In recent years, various motor and perceptual laboratory tasks have been performed to study the cognitive processes and neural substrates that mediate our capacity to acquire and retain new skills (for a review, see Censor et al., 2012). In both children and adults, the evolution of skilled performance extends beyond the actual training experiences (e.g., Adi-Japha, Badeer, Dorfberger, & Karni, 2014; Dorfberger et al., 2007). Significant training-dependent gains in performance can appear hours after training is terminated, for example 24 h post-training (Astill et al., 2014; Savion-Lemieux et al., 2009). It was proposed that these delayed, 'offline' gains-in-performance reflect neuronal memory consolidation processes triggered by the training experience, but which require time to reach completion. Consolidation processes allow the memory to become resistant to interference, and prevent its decay (i.e., forgetting) (Censor et al., 2012). Resultant gains were maintained for weeks (e.g., Korman, Raz, Flash, & Karni, 2003).

The learning of skills is addressed by the long-term procedural memory system. Long-term memory stores information for long periods (weeks, months and years), and is based on neural mechanisms that differ at least partially from those used by short-term memory (minutes scale), or by the executive system (Atkinson & Shiffrin, 1968; Squire, 2004). Within the classification of long-term memory systems, declarative memory deals with facts and events (*what* knowledge), while procedural memory is a form of non-declarative memory serving to acquire and retain skills and habits (*how-to* knowledge)—specifically,

* Corresponding author at: School of Education, Bar-Ilan University, Ramat-Gan 52900, Israel.
E-mail address: Esther.Adi-Japha@biu.ac.il (E. Adi-Japha).

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the repetition-dependent, implicit, knowledge of the structure of recurring experiences (Brown & Robertson, 2007; Cohen & Squire, 1980).

Motor skill learning refers to the process by which movements are executed more quickly and accurately with practice (Willingham, 1998), and has mostly been studied in adults. A mere handful of motor skill learning tasks have been studied in children aged 5- to 8-years: (1) The Serial Reaction Time task (SRT, Nissen & Bullemer, 1987), in which participants respond to the appearance of four stimuli that follow a rule unknown to the participant or a sequential order that is hard-to-follow (Hodel, Markant, Van Den Heuvel, Cirilli-Raether, & Thomas, 2014; Janacsek, Fiser, & Nemeth, 2012; Savion-Lemieux et al., 2009; Wilhelm, Diekelmann, & Born, 2008). (2) The Mirror-Tracing Task (Starch, 1910), in which participants trace a diagram while looking at their hand only as a reflection in a mirror (Ferrel-Chapus, Hay, Olivier, Bard, & Fleury, 2002; Julius & Adi-Japha, 2016). (3) The Invented Letter Task (ILT, Adi-Japha, Strulovich-Schwartz, & Julius, 2011), in which participants connect three dots to form an invented letter. Whereas the SRT and the Mirror-Tracing task were designed for adults, and adapted for children, the ILT was designed for kindergarten children, with minimal accuracy demands (Julius & Adi-Japha, 2015). The present study uses the ILT, comprising a to-be learned simple pattern resembling shapes commonly found in assessments of visual-motor skills (e.g., Beery, Buktenica, & Berry, 1997, ESI-R; Meisels, Marsden, Wiske, & Henderson, 1997). Copying such shapes was found to predict academic achievement (e.g., Cameron et al., 2012; Carlson, Rowe, & Curby, 2013; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Son & Meisels, 2006).

Handwriting is a perceptual-motor skill, acquired through repetitive practice (Feder & Majnemer, 2007), and is often presented as an example of a motor skill acquired via procedural learning processes (Dayan & Cohen, 2011; Wilhelm, Prehn-Kristensen, & Born, 2012). Handwriting production is most often characterized by performance speed (also termed 'production fluency', often assessed using text-copying tasks e.g., Graham, Struck, Santoro, & Berninger, 2006; Hatcher, Snowling, & Griffiths, 2002; Sumner, Connelly, & Barnett, 2014) and legibility. Studies have found that handwriting legibility develops quickly during first-grade (ages 6- to 7-years), reaching a plateau by second-grade (Overvelde & Hulstijn, 2011). By third-grade, handwriting becomes automatic, organized, and available as a tool to facilitate the development of ideas. However, handwriting is not a straightforward motor skill (Cheng-Lai, Li-Tsang, Chan, & Lo, 2013; Planton, Jucla, Roux, & Démonet, 2013), and has been linked with reading development (Berninger, 2009). Measures of motor proficiency that correlate with handwriting production in school aged children show an indirect effect on handwriting via reading related skills, such as orthography (Berninger, 2009; Abbott & Berninger, 1993), underscoring reading as a mediator of the association between motor proficiency and handwriting production.

Reading is a cognitive process that involves decoding visually presented symbols. Fitzgerald and Shanahan (2000) describe the procedural components that contribute to reading development as being able to access and use pragmatic, semantic, graphophonic, and syntactic knowledge, while integrating the processes to allow fluent reading. Reading development also involves building efficient visual-motor routines (Breznitz et al., 2013). Typical children learn basic reading mechanics in the first two years of school. There is clear evidence that reading speed can serve as indication of reading fluency, the latter needed to produce successful comprehension (Carver, 1990; Fuchs, Fuchs, Hosp, & Jenkins, 2001; possibly due to reducing cognitive load, LaBerge & Samuels, 1974; Sweller, Van Merrienboer, & Paas, 1998).

Julius and Adi-Japha (2015) assessed the ILT production in typically developing children aged 5- to 8-years. The children were trained on the ILT, and measures were taken at four time points: initial training and end-of-training (initial acquisition), 24 h post-training (consolidation phase), and 2 weeks post-training (retention). The children produced the pattern more quickly with training. Additional, consolidation phase, gains exhibited at 24 h post-training were well retained 2 weeks later. Children maintained their accuracy throughout the two-week period. *The current study*, conducted over two years (Phase I and Phase II), focuses on the sequential association of the different performance measures of the writing-like ILT to handwriting (copying speed and legibility), and reading speed. Immediately following the last ILT session, in Phase I of the study, the children were assessed for handwriting. In Phase II, conducted the following year, the children were assessed for handwriting as well as for reading speed. Reading was assessed once the youngest children finished first-grade (when children are expected to acquire reading; Linguistic Education in the First and Second Grade, 2014). The associations of ILT production to handwriting and reading were studied beyond age and socio-economic status, variables strongly associated with reading.

Previous studies of motor skill learning in children with language impairments and dyslexia did not necessarily identify deficits in the children's initial level of performance. Rather, the deficits were expressed following a consolidation period, 24 h post initial training (Adi-Japha & Abu-Asba, 2014; Adi-Japha et al., 2011; Hedenius et al., 2011; Vicari et al., 2005). Following these findings, we hypothesized that although the initial performance on the ILT, which relies on visual- and fine-motor aspects, would be associated with handwriting and reading, the association of task performance at 24 h post-training would be even greater. Furthermore, following the studies stressing the role of reading as a mediator of the association between motor proficiency and handwriting production (Abbott & Berninger, 1993), we hypothesized that Phase II (following-year) reading would mediate the association between Phase II handwriting and Phase I ILT assessment.

2. Methods

2.1. Participants

Fifty-six children, participants of the Julius and Adi-Japha (2015) study, took part in the current study as well. These included 36 children ending kindergarten (age-range 67–80 months, *Median* = 75 month, 25th–75th percentile 72–77 months, 18 girls), and 20 children about to complete second-grade (age range 90–107 months, *Median* = 95 month, 25th–75th percentile 92–99 months, 10 girls). The children's school district SES was either middle (SES = 5/10) or high (SES = 8–9/10). as reported in the census publications (Ministry of the Interior, 2013).

All the children were reported by their parents to be monolingual Hebrew speakers and were right-handed ($M = 0.88$, $SD = 0.10$; Hand Dominance Questionnaire, Oldfield, 1971). According to parental reports, the children recruited for the study did not have any known neurological conditions or sleep disorders. Furthermore, kindergarten teachers and schoolteachers identify children at risk for developmental delay in the first 3 months of the school year (Ministry of Education, 2007). The identified "at risk" children were not included in the study. Approval was obtained from the Ministry of Education (10.32/235/2010, 10.32/514/2011). Children's parents signed a consent form.

Of the 56 children, two children asked not to continue to Phase II the following year, two mothers did not sign the Phase II consent form, and three children who had moved were not located. Mann-Whitney U tests showed no significant difference in age or SES, nor in the scores of the Phase I measures in the children who did or did not participate in Phase II, the following year.

2.2. Measures

2.2.1. Age and socioeconomic status (SES)

Age and SES were used as covariates. Age at first assessment was used as a covariate because raw scores were used in the regression analyses. Children's SES was determined according to the school district. SES, and was defined as a binary variable (middle/high).

2.2.2. The beery-VMI

The Beery-VMI (Beery et al., 1997) is a standardized test that evaluates visual-motor integration skills (often associated with copying, e.g., Ogawa, Nagai, & Inui, 2010) for children aged 2-years to adult. Participants copy progressively difficult geometric shapes. The test is stopped after subjects fail to correctly copy three consecutive shapes. The final score is the number of correct shapes copied.

2.2.3. The number recall

In the Number Recall test (KABC; Kaufman & Kaufman & Kaufman, 1983), the experimenter reads aloud a random string of numbers between two and seven digits in length. The children repeat the string in the same order. Testing continues until the child makes three consecutive errors.

2.2.4. The hand movement test

In the Hand Movement test (KABC; Kaufman & Kaufman & Kaufman, 1983), children are presented with a random sequence of hand movements (made with the fist, palm, or side of the hand) of varying lengths (between two and five movements), and asked to imitate the movements. Testing continues until the child makes three consecutive errors.

2.2.5. The ILT

The ILT (Adi-Japha et al., 2011) was used to study the time-dependent course of motor skill acquisition. The task consists of point-to-point planar movements (Fig. 1A: A→B→C, segment length 1.2 cm, circle outer diameter 3 mm, shape width 6 mm) to form an invented letter. Movement progression within a block (Fig. 1B) was from right-to-left (as in Hebrew writing). Participants perform the writing-like task using an ink stylus resembling a ballpoint pen, which leaves a visible ink trace on the page. Overall, 20 blocks of the task were performed; 12 on the first (training) day, four blocks the following day, and an additional four blocks on the 2 weeks post-training day. Each block contained fifteen repeats of the same pattern. Blocks were separated by 15–30 s. The ILT speed and accuracy data used here were taken from a developmental study focusing on the kinematics of the task (Julius & Adi-Japha, 2015), and therefore the task will only be presented briefly.

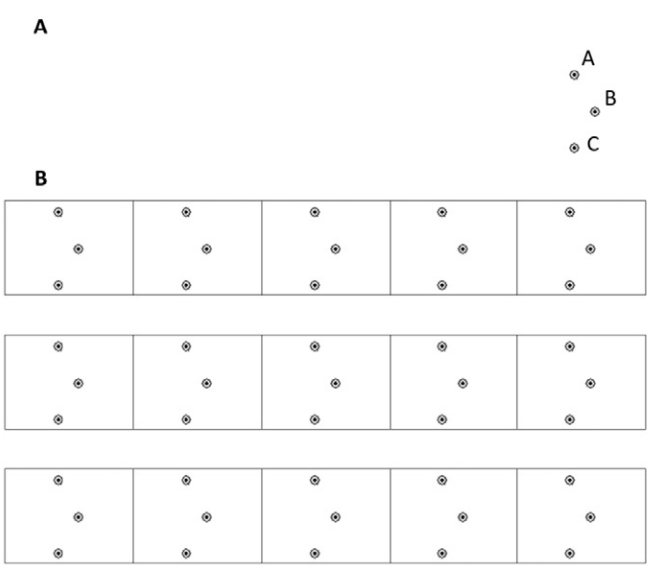

Fig. 1. The Invented Letter Stimuli. (A) A single stimulus. Writing direction A-B-C. (B) A block of the invented letter task. The writing direction was initiated from right-to-left.

2.2.5.1. Analyses

2.2.5.1. Analyses. The writing product was evaluated for speed and accuracy using a proprietary MATLAB computer program. Production time was computed from the first touch of the pen-tip to the page until task completion. Erroneous shapes included shapes that were not produced in one continuous movement (e.g., a shape composed of two segments) or shapes that were too narrow or wide with respect to the midpoint of the shape (point 'B', Fig. 1A).

Repeated measures Analysis of Variance (ANOVA) was used to study ILT performance. Four testing points, spanning the two-week period, were used in the analysis: (a) initial training (blocks 1–4 on Day 1), (b) end-of-training (blocks 9–12 on Day 1), (c) at 24 h post-training (4 blocks, assessed on Day 2, at 24 h post-training), and (d) at 2 weeks post-training (4 blocks, assessed two weeks after Day 1).

2.2.6. Handwriting speed and legibility

Handwriting speed was computed as the number of letters produced per minute in a copying task. Handwriting legibility scores were based on spatial relations. Coding was calculated based on the criteria from the Hebrew Handwriting Evaluation (HHE; Erez, Yochman, & Parush, 1996). This is a standardized assessment enabling the evaluation of speed, efficiency, and quality of handwriting for children in second-grade and above. Four measures were used in kindergarten (letter size, letter spacing, alignment with respect to the right margin, and horizontal alignment), and two additional measures were used in first- to third-grades (word spacing and writing with respect to the left margin). The assessment of the measures was done using a 4-point Likert-type scale (the lower score being the best performance, and the higher score being the worst), and then averaged.

In Phase I, the kindergarten children copied 10 familiar words, which they first read aloud (on average, children read 5.39 words, ranging from 0 to 10). Although writing tests for kindergarteners are not standardized, testing kindergarten children in Israel includes reading and writing tasks of familiar words (Share & Blum, 2005; Shatil, Share, & Levin, 2000).

In Phase II, these children (now in first-grade) were assessed for handwriting speed and legibility, using a text taken from the Shani, Biemiller, and Ben-Dror test of basic reading and writing assessment (reported in Shani, Zeiger, & Ravid, 2001). This is a standardized assessment that includes first- to sixth-grade reading and spelling assessments. Children first read a Level 1 paragraph matched for their reading ability (on average, children read 54.79 words/min, $SD = 26.30$), and were then requested to copy it. Handwriting was assessed based on the text copied within 1 min.

Children who were second-graders in Phase I, and third-graders in Phase II, were assessed in Phase I and II using the HHE (Erez et al., 1996). The to-be copied paragraph includes all the letters of the alphabet. The number of letters copied in the first minute was used as a measure of writing speed. Legibility scoring was based on the text copied up to the 107th letter, as indicated in the HHE evaluation test (for more details see, Rosenblum, Weiss, & Parush, 2003). Inter-rater reliability obtained for the writing samples of 18 children (~35% of the data) based on two independent raters was 0.80 (interclass correlation).

2.2.7. Reading speed

First- and third-graders were assessed for reading speed using the Level 1 reading paragraph from the Shani, Biemiller, and Ben-Dror basic reading and writing assessment (Shani et al., 2001). The paragraph was read aloud by the child, and the number of words read per minute was calculated.

2.3. Procedure

Children were assessed in the morning hours (8:45–11:30, either during the school day, or during school vacations). Rewards consisting of school supplies (e.g., markers and stickers) were distributed at the end of each experimental day.

In Phase I, the ILT training session took approximately 25 min for the kindergarteners and 20 min for the second-graders. The other two ILT sessions took up to 5 min. Following the last ILT session, the children were assessed on the Beery-VMI and the two short-term memory tests, and then performed the handwriting assessment. This session took up to 20 min. They were typically glad to participate in the study, but needed more encouragement toward the end of longer sessions. In Phase II, the following year, testing consisted of a single 15-min session, in which writing skills and reading speed were individually assessed.

2.4. Data analysis

Potential predictor variables assessed on Phase I of the study included the Beery-Buktenica Developmental Test of Visual-Motor Integration; two sequential short-term memory tests from the sequential subtest of the Kaufman Assessment Battery for Children: the Number Recall Test and the Hand Movement Test; and the Invented Letter Task (ILT). Outcome measures included copying speed and legibility assessed in Phase I and again the following year, in Phase II, plus reading speed assessed in Phase II.

Age at initial assessment and SES were held constant in hierarchal regressions that examined the association of the predictor variables (including ILT) to Phase I and II outcomes. Only variables correlating with the outcomes above age entered the regression analyses. Due to the non-normal distribution of some of the variables, all associative testing procedure (correlations, regressions, mediation) were based on the bootstrapping, a distribution-free method of analyses (Varian, 2005). Analyses were performed using the SPSS bootstrapping procedure (1000 repeats).

The original dataset included the standardized Beery-VMI score, the number recall test, and the hand movement test from the KABC (assessed in Phase I), an age groups variable, and age at Phase II assessment. Based on the relatively small amount of missing data (2.5%, see Table 1), the SPSS Expectation-Maximization (EM) iterative algorithm was used. EM uses all available data to estimate parameters; thus, all 56 children in the sample were retained in the analyses (Schafer & Graham, 2002). Data imputation is a common procedure in longitudinal studies. Preliminary analyses verified that the imputed dataset retained the same trends as the data before imputation. For simplicity, only the analyses of the imputed dataset are reported.

Table 1
Descriptive statistics for all variables.

	Assessment	N	M	SD
Female		56	(50%)	0.5
School district SES (0/1)	Phase I	56	0.75	0.44
Age at assessment (months)	Phase I	56	82.10	11.37
ILT—init. training speed (sec.)	Phase I	56	39.93	12.67
ILT—end training sp. (sec.)	Phase I	56	32.03	8.77
ILT—24 h post-training sp. (sec.)	Phase I	55	28.61	8.78
ILT—2w post-training sp. (sec.)	Phase I	53	28.99	7.91
ILT—init. training acc. (# err./15)	Phase I	56	2.00	1.97
ILT—end training acc. (# err./15)	Phase I	56	2.65	1.45
ILT—24 h post-training acc. (# err./15)	Phase I	55	2.00	1.77
ILT—2w post-training acc. (# err./15)	Phase I	53	1.69	1.18
Beery-VMI	Phase I	56	14.59	2.28
Beery-VMI std.	Phase I	56	97.95	9.73
Kaufman-Number recall	Phase I	56	13.02	2.75
Kaufman-Hand movement test	Phase I	56	15.89	3.33
Handwriting speed (letter/min.)	Phase I	56	20.23	13.52
Handwriting-legibility (1–4 scale)	Phase I	56	1.78	0.52
Age at 2nd assessment (months)	Phase II	56	94.48	12.34
Handwriting speed (letter/min.)	Phase II	49	35.13	19.18
Handwriting-legibility (1–4 scale)	Phase II	49	1.63	0.37
Reading speed (words/min.)	Phase II	49	75.23	34.03

Phase I = contemporaneously with the ILT. Phase II = the following year. SES = Socio-Economic Status: 0 = medium, 1 = high. ILT = Invented Letter Task. init. = initial. 24 h = 24 h. 2w = 2 weeks. Sp. = speed. Acc. – accuracy. Err = error. Legibility score = 1 best, 4 worst. Beery-VMI = the Beery-Buktenica developmental test of visual motor integration. Raw scores are reported for the Beery-VMI, Kaufman-Number Recall and the Kaufman-Hand movement tests. Age at Phase II assessment is reported for all participants, although only 49 of 56 children were assessed.

3. Results

Descriptive statistics of the study measures is reported in Table 1.

Repeated measures ANOVA applied to the four ILT speed and error performance measurements (initial, end-of-training, 24 h post-training, at 2 weeks post-training) indicated an overall improvement for the speed component ($F(3, 165) = 59.36$, $p < 0.001$, $\eta^2 = 0.52$) and retention of error rate ($F(3, 165) = 0.39$). Post-hoc analysis using Bonferroni correction indicated that performance-speed improved from initial training, to end-of-training (training gains), to 24 h post-training (consolidation gains, 24 h vs. end training) ($ps < 0.001$), and was well retained 2 weeks later. Training gains (end-of-training vs. initial performance) did not correlate with consolidation gains (24 h post-training vs. end-of-training). Error scores were maintained, therefore an averaged error score was used in later analyses.

Preliminary inspection of the outcome data indicated that there were no gender differences in the predictor measures or outcome test scores, except for Phase II legibility (girls wrote more legibly, $t(54) = 1.99$, $p < 0.05$). Paired sample t-tests indicated that children improved their writing skills between the Phase I and Phase II (speed: $t(55) = 11.76$, $p < 0.001$; legibility: $t(55) = 2.21$, $p < 0.03$).

Partial correlations among predictor variables and among predictor and outcome variables, controlling for the age of ILT assessment were held to verify which variables would enter regression analyses (Table 2, 95% CI are reported for significant associations). Initial analysis indicated that children's scores on the KABC short-term memory measures were not significantly associated with the outcomes beyond age; therefore, these associations are not reported.

3.1. Associations between the ILT and handwriting legibility scores

Based on the associations reported in Table 2, a regression analysis with the age at Phase I assessment and SES entered on the first step, and the visual-motor integration test and average error rate entered on the second step, was applied to the Phase I legibility score. Results indicated that the Beery-VMI and the averaged ILT error rate were significant predictors (Bootstrapped coefficients, Beery-VMI: $B = -0.084$, $SE = 0.03$, $p < 0.03$, $\Delta R^2 = 0.09$; Averaged error rate: $B = -0.12$, $SE = 0.06$, $p < 0.05$, $\Delta R^2 = 0.06$, Overall $R^2 = 0.31$). None of the predictor variables was associated with Phase II handwriting legibility; therefore, this outcome measure was not studied further.

3.2. The ILT in relation to handwriting- and reading-speed

As can be seen in Table 2, the four ILT speed measurements (but not error score) contributed to the three dependent measures, above age. These variables were therefore used in all the analyses. Table 3 indicates the results of an overall multivariate analysis across outcomes (first column) followed by hierarchal regressions pertaining to the three dependent measures (columns 2–4).

In the analyses presented in Table 3, age at Phase I assessment and SES were entered at the first step, and the four ILT speed measurements added in pairs by their sequential order, in a second and third step. In each model (Models 1–4), the table specifies the results of the three steps, and their added explained variance. For example, Model 1 step 3 specifies the additional contribution of the end-of-training ILT measurement beyond the contribution of initial training. This contribution denotes the contribution of the training gains (online gains. i.e., gains accrued from initial to end-of-training) above that of initial performance.

Table 2
Partial correlations among predictor variables and among predictor variables and outcome variables controlling for age at Phase I assessment.

Variables	Phase I assessment			Phase II assessment		
	Beery	Writing		Writing		Reading
	VMI	Speed	Legibility	Speed	Legibility	speed
Phase I assessment						
SES	***0.30 [0.09, 0.50]***	0.08	−0.28	0.14	−0.19	***0.51 [0.30, 0.69]***
Berry-VMI	–	0.14	***−0.39 [−0.61, −0.15]***	0.13	−0.13	0.23
ILT averaged error score	−0.13	0.05	***0.27 [0.01, 0.53]***	−0.08	0.23	−0.05
ILT init. training sp.	0.01	***−0.30 [−0.49, −0.10]***	0.01	***−0.31 [−0.51, −0.08]***	0.04	***−0.40 [−0.57, −0.20]***
ILT end training sp.	0.08	***−0.46 [−0.66, −0.24]***	0.01	***−0.46 [−0.66, −0.22]***	0.01	***−0.41 [−0.62, −0.15]***
ILT 24 h post training sp.	−0.08	***−0.52 [−0.67, −0.38]***	−0.02	***−0.50 [−0.71, −0.28]***	−0.16	***−0.46 [−0.65, −0.21]***
ILT 2w post training sp.	−0.10	***−0.39 [−0.38, −0.15]***	0.10	***−0.46 [−0.66, −0.21]***	0.13	***−0.37 [−0.61, −0.09]***

Coefficients' estimates appearing in Table 2 are based on a bootstrapping procedure, 95% confidence interval (CI) is reported only for significant associations. For example, the partial correlation (controlling for age) of SES and the Beery-VMI is 0.30. The CI for this correlation extends from 0.09 to 0.50 [in brackets]. Significant correlations appear in bold italics.
Phase I = contemporaneously with the ILT. Phase II = the following year. SES = Socio-economic status: 0 = medium, 1 = high. ILT = Invented Letter Task. Error scores were maintained; therefore, an averaged error score across the task was computed. Init. = initial. 24 h = 24 hours. 2w = 2 weeks. Sp. = speed. Legibility score = 1 best, 4 worst. Beery-VMI = the Beery-Buktenica developmental test of visual motor integration.

The multivariate analysis (first column) indicated that end-of-training performance-speed was significantly associated with the outcomes above initial training performance-speed (Model 1, Step 3); and that 24 h post-training performance-speed was significantly associated with the outcomes above end-of-training performance-speed (Model 2, Step 3). Two weeks post-training speed did not contribute to the outcomes above the contribution of the 24 h post-training performance-speed (Model 3, Step 3). Model 4 indicates that 24 h post-training performance-speed was significantly associated with the outcomes above initial training performance-speed. Differently stated, Model 4 accounts for the combined contribution of the training gains and the consolidation-phase gains, above the contribution of initial performance.

The second column specifies contributions to Phase I handwriting speed. Background variables (age and SES) explained 63% of its variance (Step 1). The added contribution of the ILT initial performance-speed is 4% (Model 1, Step 2). ILT end-of-training performance-speed contributed an additional 5% to the variance (Model 1, Step 3), thus training gains added 5% to the variance above initial performance. The 24 h post-training performance-speed contributed 3% to the variance above end-of-training speed (Model 2). These 3% represent the contribution of 24 h post-training performance vs. end-of-training performance (offline, consolidation phase, gains). The 2 weeks post-training performance-speed did not contribute beyond the contribution of the 24 h post-training performance-speed (Model 3). Step 3 in Model 4 shows that 24 h performance-speed added 7% to the variance above the 4% contributed by initial level performance-speed. The third and fourth columns specify contributions to Phase II handwriting- and reading-speed, respectively.

The findings presented in Table 3 indicate that for all three outcome variables, the end-of-training measurement and the 24-h post-training measurement contributed more than their preceding components. A stepwise regression verified that the 24-h post-training measurement made the largest contribution to the outcomes among all 4 ILT speed measurements. As hypothesized, for all outcome measures, the 24-h post-training measurement significantly added to the explained variance above the initial training measurement (Model 4, all $ps < 0.02$). This contribution was, however, only of a small magnitude. Altogether, the contribution made by Model 4 was of a medium effect-size (~10%). To ensure that the results reported in Table 3 were not due to the correlation between the ILT components, each regression was repeated by entering the ILT components in the reverse order (National Institute of Child Health and Human Development Early Child Care Research

Table 3
Hierarchical regression—predicting handwriting and reading speed by ILT performance level.

	F overall	Phase I handwriting speed			Phase II handwriting speed			Phase II reading speed		
	df = (3,49)	B	SE	ΔR^2	B	SE	ΔR^2	B	SE	ΔR^2
Step 1				0.63			0.72			0.60
Age	37.83***	0.93***	0.09		1.35***	0.13		1.63***	0.27	
SES	7.37***	1.62	2.12		3.46	2.65		29.44***	6.47	
Model 1										
Step 2 ILT init. training sp.	7.95***	−3.43*	1.46	0.04	−4.43*	1.69	0.03	−14.86***	2.49	0.12
Step 3 ILT end training sp.	3.51*	−6.99***	1.95	0.05	−8.38**	2.75	0.04	−6.74	5.85	0.01
Model 2										
Step 2 ILT end training sp.	8.96***	−5.93***	1.52	0.08	−6.78***	1.78	0.06	−14.67***	3.33	0.12
Step 3 ILT 24 h post training sp.	3.3*	−4.15*	1.93	0.03	−4.86*	2.28	0.02	−10.79*	4.09	0.04
Model 3										
Step 2 ILT 24 h post training sp.	12.73***	−5.44***	1.51	***0.11***	−6.56***	1.93	***0.08***	−14.79***	2.66	***0.14***
Step 3 ILT 2w post training sp.	1.42	−0.41	1.68	0.00	−2.02	2.06	0.00	4.94	5.01	0.00
Model 4										
Step 2 ILT init. training sp.	7.95***	−3.43	1.46	0.04	−4.43*	1.69	0.03	−14.86***	2.49	0.12
Step 3 ILT 24 h post training sp.	5.57**	−6.12**	1.51	0.07	−7.02**	2.09	0.05	−9.98*	3.88	0.03
Model 4: Total R^2				0.74			0.80			0.75

Coefficients' estimates appearing in Table 3 are based on a bootstrapping procedure. In the overall multivariate analysis (Column 1), all ps < 0.025 (Bonferroni correction for the comparison of two ILT components). *B* = unstandardized regression coefficient (*B* + Bootstrap bias); *SE* = standard error of *B*.
Note. In each model, the contribution to the variance of the later measurement above the preceding measurement, is equivalent to the contribution of the gains made between measurements above the contribution of the preceding measurement (e.g., the contribution of speed training gains to Phase I handwriting speed is 5%, Model 1, step 3). The ILT component that made the largest contribution is indicated in bold italics.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Network, 2005). Results indicated that earlier ILT components did not contribute above later ILT components.

While interpreting these findings it should be noted that training gains per-se (as well as consolidation-phase gains) were not associated with the outcomes. Rather, these findings indicate that gains in performance explained a significant portion of the variability that remained after accounting for the variability explained by the preceding performance measurement. For example, a multivariate analysis across outcomes indicate significant effects for training gains and consolidation gains ($ps < 0.01$, 0.03, $\eta_p^2 = 0.27$, 0.17, respectively) when tested *after* accounting for the contribution made by initial performance (age and SES controlled, $p < 0.001$, $\eta_p^2 = 0.41$). A stepwise regression (age and SES controlled) showed that when comparing between the contribution of initial performance and later gains to Phase I and II handwriting speed, initial performance-speed made the largest contribution, followed by training gains, followed by consolidation gains (all $ps < 0.02$). For Phase II reading, the separate contributions of the training- and consolidation-gains did not reach significance level.

3.3. Reading speed as a mediator

To test the idea that Phase II reading speed mediates the association between ILT performance-speed and Phase II handwriting speed, a test of mediation was conducted. For brevity, we only specify the analysis for the first ILT speed-measurement, but results were the same for all four ILT measurements.

It was confirmed that reading speed was significantly associated with handwriting speed even when tested with the initial ILT performance-speed as a predictor ($B = 0.31$, $SE = 0.06$, $p < 0.001$; age and SES controlled), while initial ILT performance-speed was not. An estimation of the indirect effect (using bootstrapping, Shrout & Bolger, 2002) indicated that the indirect coefficient was significant ($B = -4.73$, $SE = 1.42$, 95% $CI = -7.68$, -2.28). Therefore, initial ILT performance-speed was associated with Phase II handwriting speed, via Phase II reading speed.

4. Discussion

In the current study, 5- to 8-year-old children's handwriting and reading were associated with the production of the ILT, a simple, graphomotor skill learning task. In Phase I of the current study, children's handwriting (speed and legibility) was assessed contemporaneously with the ILT. The following year, Phase II assessed both handwriting and reading speed. The findings clearly indicate that the performance of the ILT showed strong associations to handwriting and reading.

The ILT averaged accuracy score was associated with handwriting legibility, assessed contemporaneously with the ILT, beyond age, SES, and visual-motor skills All four ILT speed-performance measurements were associated with contemporaneous handwriting speed, as well as with handwriting- and reading-speed assessed in the following year, beyond age and SES. Of the four ILT speed-performance measurements, 24 h post-training measurement made the largest associations. While age and SES contributed 60%–70% to the handwriting- and reading speed variance, an additional 10% (or larger) contribution was made by successive ILT speed measurements. Finally, the association between ILT speed-performance measurements and following year handwriting speed was mediated by reading speed assessed contemporaneous with handwriting speed. We suggest that the results reflect the role of the underlying procedural learning mechanism in handwriting and reading, as assessed using the ILT.

Previous studies have established that fine-motor perceptual performance predicts reading (Cameron et al., 2012; Grissmer et al., 2010; Pagani, Fitzpatrick, Archambault, & Janosz, 2010; Son & Meisels, 2006) beyond the long-established contribution of executive function (Duncan et al., 2007). For example, in an analysis of several longitudinal, large-scale databases, Grissmer et al. (2010) found that performance on a copy design test in kindergarten predicted reading in fifth-grade, beyond early reading, attention, family, and child characteristics. In the current study ILT speed measurements were associated with handwriting and reading. Perhaps this association is related to the finding that similar brain regions are involved in learning perceptual-motor, motor, linguistic, and other cognitive skills. Furthermore, impaired functioning of some of these regions or networks may underlie deficits in handwriting and reading (Nicolson & Fawcett, 2011).

Similar training effects and learning stages were found in laboratory motor-, linguistic-, handwriting-, and reading-learning tasks (Bitan & Karni, 2004; Bitan & Booth, 2012; Ferman & Karni, 2010; Morgan-Short et al., 2010; Rosenbaum, Carlson, & Gilmore, 2001). The current study extends these previous studies by showing that the *processes* of learning (i.e., improvement beyond initial performance) is reflected in real-life domains, such as handwriting and reading (see Adolph & Robinson, 2008, for processes vs. outcomes measures). ILT contributions reflected the additive nature of skill-learning processes. Initial performance speed contributed to explaining outcome measures; training gains made an additional contribution (Table 3, Model 1). End-of-training performance speed contributed to explaining outcome measures; consolidation gains made an additional contribution (Table 3, Model 2). No additional contribution was made by the 2 weeks post-training speed performance measure above that of the 24 h post-training performance (Table 3, Model 3). Arciuli and Simpson (2012) reported an association between achievements following one session of statistical learning—a form of non-declarative, implicit, learning and contemporaneous reading achievements, beyond age, in a sample of thirty-eight 6- to 12-year-olds. Future studies should look for associations between academic achievements and the process of skill learning in extended training paradigms (Adi-Japha & Abu-Asba, 2014).

Previous studies did not always find clear indications of the association between motor skills and handwriting speed in typical, primary-school-aged children. Because motor skills are specific (Goodenough, 1935), it is difficult to know which motor proficiency to assess when evaluating the underlying process (Abbott & Berninger, 1993). The ILT shares basic motor and visou-motor proficiencies and procedures (e.g., pattern formation, identification and movement direction) with reading and handwriting, like previous tasks found related to academic achievements (Abbott & Berninger, 1993; Roebers et al., 2014; Ho, 2011). The ILT, like reading and writing, requires the parsing of discrete elements, and horizontal progression between elements (as in the writing system). We believe that the indirect path associating ILT performance with handwriting speed via reading speed found here reflects these similar underlying processes shared among handwriting and reading.

Handwriting legibility is mostly cited to reflect the development of visual-motor integration skills captured by the Beery-VMI (Feder & Majnemer, 2007). Some studies report that VMI is correlated with writing legibility in typically developing children (Daly, Kelley, & Krauss, 2003). However, other studies have not fully confirmed this finding (Marr & Cermak, 2002; Volman, van Schendel, & Jongmans, 2006). For example, Marr and Cermak (2002) conducted a longitudinal study on kindergarten children, and found that VMI did not predict writing legibility a year later. The findings of the current study support the notion that the Beery-VMI is associated with contemporaneous handwriting-legibility, but does not predict performance in the following year. This may suggest that test scores reflect the current motor-control strategy, and cannot predict behavior when execution strategy changes between the ages of 5- and 7-years (Ferrel-Chapus et al., 2002). The averaged ILT accuracy predicted contemporaneous legibility, possibly because accuracy measures reflect attentional/declarative task elements (Janacsek et al., 2012).

4.1. Limitations and future directions

The current study is a small-scale, correlational study. As well as ILT production, other factors not studied here (e.g., maternal education, non-verbal intelligence, child attention, and quality of sleep) may have affected academic achievements. Furthermore, although none of the participating children were known to have a neurological disorder or a sleep problem, they may be diagnosed later.

We used specific measures to evaluate grapho-motor proficiency, handwriting, and reading speed. Other measures may have produced different results. Future research with larger samples and a wide range of child, family, and educational environment covariates should be used to further study the associations reported here.

Current studies assess motor skills with relation to academic achievements (e.g. Cameron et al., 2012) by using tasks familiar to children (e.g., copy of familiar shapes). It is suggested that a more controlled measure of motor skills be used, because children's histories of task familiarity vary, making it difficult to differentiate initial ability from gains achieved through practice.

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