Psychology of Sport & Exercise 55 (2021) 101954

Contents lists available at ScienceDirect

Psychology of Sport & Exercise

journal homepage: www.elsevier.com/locate/psychsport

New insights into visual-motor integration exploring process measures during copying shapes

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A R T I C L E I N F O

Keywords:
Copy design
Visual-motor integration
Executive functions
Manual dexterity
Motor learning
Children

A B S T R A C T

The link between visual-motor integration (VMI) and executive functions (EF) has been repeatedly documented in preschool children. VMI is often assessed using the Copy Design task measuring the product, thereby neglecting the processes that lead to a specific copy. Furthermore, EF are assumed to be mainly involved when a task is new. The involvement of EF after minimal practice in VMI, however, is unknown. Therefore, the present study investigated product- (i.e., accuracy) and process-based measures, namely velocity, and fluency, in five consecutive trials of copying shapes. Contributions of manual dexterity and EF to both VMI product and VMI processes across five trials were investigated in a sample of 5- to 6-year-old kindergarten children. Results revealed that children did not copy the shapes more accurately across the five trials, but quicker and more fluently. In line with previous findings, children's performance on VMI, manual dexterity, and EF were interrelated. The results indicate that over and above the copy's accuracy, also fluency of copying is a crucial indicator of VMI, which is related to EF and manual dexterity. Furthermore, findings on the VMI–EF link point to strong EF involvement during copying when the task is new and to a decreasing EF involvement with increasing practice, already after five trials. New insights into VMI in preschool children are discussed with regard to underlying cognitive processes.

1. Introduction

When children learn to write, they usually face multiple challenges. These challenges include remembering the shape of a certain letter, continuously integrating visual and motor information while writing, and simultaneously planning, adjusting, and controlling fine motor movements. Successful coordination of all these elements enhances fluent, automatic, and legible handwriting (Feder & Majnemer, 2007). Children usually start scribbling, followed by drawing and copying with increasing precision and control. Copying shapes is considered a precursor or prerequisite for copying letters (Dinehart, 2015), which typically represents the opening of handwriting instruction. At the beginning of handwriting acquisition, writing a shape or letter requires extensive attention, fine motor control, planning, and visual-motor integration skills. Cognitive processes seem to be especially involved in these early phases, when a motor task is new and attention-demanding (e.g., Ackerman, 1988; Diamond, 2000; Roebers & Kauer, 2009). However, besides the product (i.e., accuracy) of copying, little is known about a) the processes during copying (e.g., velocity and fluency) and b) the cognitive involvement in the early phases of copying shapes. The present study investigates early motor learning across five trials on copying geometric shapes and explores the contribution of manual dexterity and EF to product and process measures of VMI in 5- to 6-year-old children.

The acquisition of motor skills through repeated practice, also known as procedural learning, describes the processes by which a specific task or skill can be performed quicker and more accurately with practice (Willingham, 1998). Motor learning follows three different stages, originally described by Fitts (1964), and adapted by Doyon et al. (2003). In the first stage of motor learning, performance improves strongly and rapidly within the first trials when an individual is exposed to a new motor task. The task procedure is being learned, and first adaptations are being made. The first stage is also called the cognitive stage, as motor performance heavily relies on cognitive control of the movements (Fitts & Posner, 1967). In the second, slow learning stage, further performance gains can be observed across days, weeks, or months of practice. Finally, in the third and autonomous stage, task performance becomes increasingly resistant to interference; the task can be performed in various

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https://doi.org/10.1016/j.psychsport.2021.101954
Received 21 April 2020; Received in revised form 22 March 2021; Accepted 18 April 2021
Available online 23 April 2021
1469-0292/

contexts with limited demands on attentional resources (Biotteau et al., 2015).

Motor learning has been investigated in children and adults using the serial reaction time task (Nissen & Bullemer, 1987), the pursuit rotor task (Hsu, 2014), the invented letter task (Adi-Japha et al., 2011), the inverted mouse task (Lejeune et al., 2013, 2016), or the mirror tracing task (Starch, 1910). Most of these motor tasks are only loosely related to children's spontaneous motor activities and used to investigate motor learning across a substantial number of repetitions. Comparatively little is known about kindergarten children's motor learning across a limited number of trials in a task they may naturally encounter, such as copying.

Findings from neuroimaging studies provide unique insights into the shared neuroanatomical and neurophysiological routes of motor and cognitive processes (e.g., Hanakawa, 2011). Specifically, brain regions important for motor and cognitive functioning were found to be co-activated during performance of new and difficult motor or cognitive tasks (Diamond, 2000). Furthermore, neural activity changes in the course of motor learning. For example, the cerebellum is most actively involved in early motor learning (Doyon et al., 2002). Cerebellar mechanisms are considered to improve motor performance (Doyon et al., 2003) by adjusting motor behaviour in response to sensory input. With practice, cerebellar activity decreases and is no longer detectable when the task or behaviour is well learned (Doyon et al., 2002).

However, not all motor tasks recruit cognitive processes. Zooming into the specific nature of the motor–cognition link, especially manual dexterity (Livesey et al., 2006; Roebers et al., 2014; Zhang et al., 2018), and visual-motor integration skills (VMI; e.g., Becker et al., 2014; MacDonald et al., 2016; McClelland & Cameron, 2019) were found to be associated with EF. Although not a uniform construct, EF are typically defined as three distinguishable yet interrelated cognitive processes: *Inhibition* of initial impulses or predominant responses, *updating* of representations in working memory, and *shifting*; the ability to flexibly adjust to changing conditions (Diamond & Ling, 2016; Miyake et al., 2000). EF processes are located in the prefrontal cortex and are especially required in novel and complex situations (Miyake et al., 2000), including new and complex motor tasks (Maurer & Roebers, 2019, 2020), like copying shapes.

Manual dexterity, on the one hand, also known under the term fine motor skills, involve coordination and control of small muscle movements, mostly of hands and fingers (Bruininks & Bruininks, 2005) with only minimal demands on visual-spatial skills (Carlson et al., 2013; Korkman et al., 1998). VMI, on the other hand, refers to the ability to coordinate visual information with a fine motor response (Beery et al., 2010) as used when copying letters or shapes. VMI requires to form and maintain a mental representation, for instance, of a shape or letter, when copying it. Copying a shape requires planning and sequencing movements, controlling force and speed of drawing, and consistently integrating perceptual and motor information. Furthermore, copying requires attending to the to-be-copied item and keeping its representation in working memory, and flexibly switching between the to-be-copied item and one's own drawing.

VMI is usually assessed with the Copy Design task (Beery et al., 2010; Bruininks & Bruininks, 2005), a paper-and-pencil task in which geometric shapes of varying difficulty are copied on a sheet of paper (e.g., Berninger et al., 1992; reading and writing; Cameron et al., 2015; motor learning; Julius et al., 2016). However, the Copy Design task focuses only on the product by evaluating the copy according to certain criteria (shape, overlap/gap, proportions, orientation, overlap, and size). It thereby neglects the processes that lead to a specific copy (as recently shown by Fears & Lockman, 2018, 2019). Although the accuracy of two products (i.e., copies), rated according to set criteria, may lead to the same score, the processes during copying may still differ substantially. The drawings depicted in Fig. 1 demonstrate how processes leading to a product may differ as indicated by rather fluent movements depicted on the left, compared to wobbly pen movements on the right. This is why this study explores both the product and the processes underlying VMI, with the latter being quantified through velocity and fluency of copying.

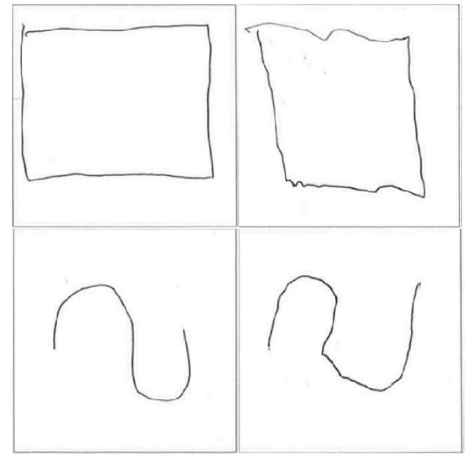


Fig. 1. Examples illustrating different VMI processes.

First efforts to investigate the processes of VMI applied ballpoint pens detecting the force between the pen tip and the paper during tracing numerals (Lin et al., 2017). Other approaches used digitising tablets (Tucha et al., 2008) or eye-tracking methods during copying (e.g., Fears & Lockman, 2018; Maldarelli et al., 2015). Specifically, Fears and Lockman (2018) examined numbers and patterns of visual fixations before and during copying letters and related children's eye movements to their ongoing hand and finger movements during copying. Their results showed that with increasing age, children needed less time to process a shape visually and less time to initiate a writing action, whereas children of all ages spent a similar amount of time writing letters and symbols (Fears & Lockman, 2018).

Young children's performance on copying geometric shapes correlates strongly with children's ability to copy letters legibly (Daly et al., 2003). In turn, handwriting legibility was found to be associated with cognitive planning skills (Volman et al., 2006). With practice, finger movements generally become more fluent, letter shapes more steady, and consequently writing (Dinehart, 2015) – and likely also copying shapes – becomes less reliant on cognitive processes. Furthermore, the ability to copy shapes is a substantial school readiness factor associated with subsequent academic achievement (e.g., Cameron et al., 2012; Carlson et al., 2013; Grissmer et al., 2010; Son & Meisels, 2006). For instance, a study in 5- to 8-year-old children showed that motor learning on a writing-like task (the inverted letter task; Adi-Japha et al., 2011), quantified with higher velocity and legibility, was related to handwriting and reading performance one year later (Julius et al., 2016). However, the processes contributing to the link between copying shapes (i.e., VMI) and school achievement are not yet understood. Before we can disentangle the link between VMI and school achievement, we need to better understand the different components of VMI and the underlying factors. Therefore, the present study investigated the contribution of manual dexterity and EF to both product and process-based measures of VMI. We used digitizing tablets to capture and investigate velocity and fluency during copying, which are relevant handwriting processes (Dinehart, 2015). Insights into the processes during copying will teach us more about the complex Copy Design task and the specific aspects of VMI that recruit EF processes.

The aims of this study were (1) to investigate early motor learning on the product (accuracy) and process-based measures of VMI (velocity and fluency) by specifically addressing the first five trials of a new task, (2) to explore the contribution of manual dexterity and EF to different measures of VMI, and (3) to investigate the VMI–EF link for different measures of VMI. We expect an interrelation of the three constructs, manual dexterity, VMI accuracy, and EF. Furthermore, we assume the VMI–EF link to be stronger in the first trial of copying, when the task is new, compared to the fifth trial. Regarding VMI processes, this study was exploratory in nature. Given the newly used process-based approach on copying shapes and the poorly investigated link between early handwriting skills and EF in preschool children (Dinehart, 2015), we did not formulate any hypothesis in this specific respect.

2. Method

2.1. Participants

Sixty kindergarten children aged 5–6 participated in the experiment. Of these, six children were excluded from the analyses due to absence on one of the testing days (n = 1), due to a reported motor disability (n = 1), or a score below the 15th percentile (n = 4) on the Movement Assessment Battery for Children (M-ABC-2; Petermann, 2011). The mean age of the remaining fifty-four children was 6 years 1 month (range = 5; 0–6; 11, *SD* = 6.61 months, 41% girls). Most children came from middle to upper-middle-class families living in urban areas, and the majority of children (85%) spoke (Swiss) German as their first language. Those who had a different first language were sufficiently fluent in (Swiss) German to follow task instructions. Before participation, written informed consent was obtained from the parents; children gave verbal assent before each session. Children were explained that they could terminate participation at any time. No child ever did. The research ethics committee of the University of Bern approved the study (2019-03-00005).

2.2. Procedure

A within-subject design was used. Trained research assistants tested children individually in a quiet room at the kindergarten. Children completed three assessments on three different days. Each assessment lasted approximately 25 min. The M-ABC-2 (Petermann, 2011) was conducted on assessment one. The remaining tasks (Copy Design, manual dexterity, and EF tasks) were split across assessments two and three. Specifically, in assessments two and three, children were randomly assigned to six different pseudo-counterbalanced task orders. As for the Copy Design task, children copied four different shapes. Each shape was copied five times in succession, with a short break between each trial, resulting in 20 copies in total. To keep children motivated, the tasks were embedded in a cover story of a treasure hunt. Children were rewarded with one stamp on their board after each task. At the end of the third assessment, when children earned the last stamp on their board, all children received a small present for participation. Using a parents' questionnaire, information about the children's health status, physical activity level, participation in structured physical activities, and the family's socioeconomic background was collected. The return rate was 84%.

2.3. Measures

Children's motor performance was broadly measured using the frequently used M-ABC-2 (Petermann, 2011), which shows good psychometric properties (Hands et al., 2015; Psotta & Brom, 2016). Motor learning on copying shapes was measured with the Copy Design task of the Bruininks–Oseretsky Test of Motor Proficiency-Second Edition (BOT-2; Bruininks & Bruininks, 2005). The BOT-2 shows high reliability (Hands et al., 2015; Wuang & Su, 2009). To assess motor learning on the Copy Design task measuring VMI, five trials were administered. Manual dexterity was assessed with three tasks: The Threading Beads (M-ABC-2; Petermann, 2011), the Pegboard (BOT-2; Bruininks & Bruininks, 2005), and the Connecting Dots task (BOT-2; Bruininks & Bruininks, 2005) — all tasks which are part of frequently used motor test batteries. Children were seated at a table with their feet flat on the floor, elbows slightly flexed, and forearms resting comfortably on the table (Penso, 1990). All tasks will be described in detail in the following paragraphs.

2.3.1. Copy Design

For the Copy Design task, children were asked to copy as accurately as possible geometric shapes of varying difficulty into a predefined field on a sheet of paper. This task measuring VMI is part of different motor test batteries. While in the widely-used Beery-Buktenica Developmental Test of Visual-Motor Integration (Beery VMI; Beery et al., 2010), the copy of each geometric shape is scored with either zero or one, in the BOT-2 (Bruininks & Bruininks, 2005), different aspects are scored, leading to a maximum score of four to six per copy. To better detect performance changes over repeated trials, the BOT-2 was used.

Four items, namely the circle, triangle, square, and curve, were copied five times within the same session to assess motor learning across consecutive trials. Children had one attempt per trial and were not allowed to correct their copy. To make sure that children actually had to look at the specific item they were to draw (instead of retrieving it from memory), the five trials of each item were not conducted in immediate succession but with two other items in between. Every item was rated concerning four to six of the following aspects: shape, overlap/gap, proportions, orientation, overlap, and size (Bruininks & Bruininks, 2005).

2.3.2. Kinematics

The Copy Design task is a paper-and-pencil task that emphasizes the task's product, that is, the accuracy of the individual's copy. A graphical tablet (Wacom Intuos PRO medium®) was used to capture processes of copying different shapes. Specifically, the paper sheets of the Copy Design task were placed on the Wacom tablet. A magnetic induction pen (Intuos5 Inking Pen®) with a regular ballpoint was used to copy the items. Data were recorded and analysed using CSWin Pro 2016® (Mai & Marquardt, 2007). Due to the magnetic induction method, the pen's position can be recorded precisely. The recording frequency was 200 Hz, and the accuracy in both the x- and the y-axis was 0.1 mm. CSWin Pro applies a non-parametric estimation of regression functions using kernel estimates to calculate velocity and acceleration signals (Marquardt & Mai, 1994). CSWin Pro has been used previously to assess handwriting kinematics (e.g., Jasper et al., 2011; Rueckriegel et al., 2008; Schabos et al., 2019).

For each trial, velocity (mm/s) and the number of inversions of velocity (NIV) were recorded to assess task performance processes. The velocity describes how quickly the pen moves on the paper when copying the items. The NIV describes the smoothness of the velocity signals within a movement sequence. This measure indicates the average number of velocity changes, that is, the fluency of a certain movement unit (Mai & Marquardt, 1999). The lower the NIV, the more fluent the movement. A movement unit with only one velocity maximum corresponds with high fluency. The assessment of handwriting kinematics has been reported to be highly objective and reliable (Rueckriegel et al., 2008).

2.3.3. Threading Beads

The Threading Beads task, part of the manual dexterity subscale of the M-ABC-2 (Petermann, 2011), was used. Children were asked to pick up cube beads one at a time and thread them on a lace as quickly as possible. The time it took to thread 12 beads on the lace was measured.

2.3.4. Pegboard

The Pegboard task is part of different motor test batteries and is assumed to measure manual coordination, specifically manual dexterity (Bruininks & Bruininks, 2005), and speed (Kail, 1991). The Pegboard task of the BOT-2 (Bruininks & Bruininks, 2005) was used. Children were asked to pick up 12 pegs, one at a time, and insert them with their dominant hand into the pegboard as quickly as possible. The time it took to place 12 pegs into the pegboard was recorded and used as a dependent measure.

2.3.5. Connecting Dots

The Connecting Dots task is part of the fine manual control composite of the BOT-2 (Bruininks & Bruininks, 2005) and measures fine motor precision. Children were asked to connect four dots with diagonal, ideally straight lines without lifting the pen from the paper. The dots build a diamond, requiring to draw four diagonal lines. The dots were 55 mm apart from each other. Children were instructed and shown to start with the bottom dot and to connect the dots counterclockwise. Performance was scored by a maximum raw score of 12, which served as a dependent measure.

2.3.6. EF

Three tasks measuring EF were included. All EF tasks were computer-based and programmed in OpenSesame (Mathôt et al., 2012). The tasks were presented on a tablet computer (12.1″ screen).

2.3.6.1. Hearts and Flowers. The Hearts and Flowers task (Davidson et al., 2006; Diamond et al., 2007) has been designed to tax both inhibition and shifting. In this task, children react to a stimulus (a heart or a flower) by pressing either the left or the right external response button in front of them. At the onset of each trial, a fixation cross was presented for 500 ms. Next, a stimulus either on the right or on the left of the screen appeared. Stimuli were presented until the child responded.

The Hearts and Flowers task consisted of three blocks of trials: a congruent, an incongruent, and a mixed block. In the congruent block (12 trials), a heart was presented either on the left or the right side of the screen. Children were instructed to respond as quickly and as accurately as possible on the same side as the heart. In the incongruent block (20 trials), a flower was presented either on the left or the right side of the screen. For this block, children were instructed to respond as quickly and as accurately as possible on the side opposite the flower (i.e., spatial conflict). Thus, during this block, children had to inhibit the dominant response of pressing the button on the same side (which was the former rule). Prior to these two blocks, instructions and practice of four trials were given. Instructions and practice trials were repeated if more than one error was made.

Mean reaction times of correct responses in the flowers block and the percentage of correct responses (accuracy) were recorded to measure inhibition. As children were instructed to perform as quickly and as accurately as possible, a score integrating speed and accuracy with equal weights was used for further analyses. We opt for the Balanced Integration Score (Liesefeld & Janczyk, 2018) as this score was shown to be relatively insensitive to speed–accuracy trade-offs. The Balanced Integration Score was calculated by subtracting standardized reaction times from standardized accuracies for each child individually. This score was used as a dependent measure for inhibition.

The mixed block of the Hearts and Flowers task (Davidson et al., 2006; Diamond et al., 2007) was used to assess the ability to shift attention flexibly. In the mixed block (40 trials; 20 hearts, 20 flowers, in fixed pseudo-randomized order), either a flower or a heart appeared on the screen. Children needed to shift between the two previously learned rules flexibly; to respond on the same side when a heart was presented, and respond to the opposite side when a flower was presented. Only verbal instructions were given prior to this block. Mean reaction times of the correct responses in the mixed block, and the percentages of correct responses (accuracy) were recorded. The Balanced Integration Score was also used as a dependent variable for shifting.

2.3.6.2. Backwards Colour Recall. Similar to a classic backwards digit span task, the Backwards Colour Recall task (Roebers & Kauer, 2009) was used to assess verbal working memory. Children were asked to memorize the sequence of coloured discs and to name the colours of those discs (items) in reverse order immediately after the last item was shown. Items were presented for 1200 ms and separated by an inter-stimuli interval of 500 ms. The task started with two items, and the sequence length was increased by one if at least three out of six sequences (50%) were remembered correctly on each sequence length. The task was terminated if recall of more than three out of six sequences of a specific span length was incorrect. Instructions and practice were repeated maximally twice if more than one error was made during practice. The total number of correctly recalled sequences across sequence lengths was used to measure verbal working memory.

2.3.6.3. Position Span. Children's visual-spatial working memory was assessed using the Position Span task (Frick & Möhring, 2016). This task is based on the Corsi Block-Tapping Task (Corsi, 1972) and was adapted for children. Embedded in a cover story, a groundhog appeared at different locations in a 4 × 4 grid. Children were asked to memorize the locations where the groundhogs had appeared and to touch these fields in reverse order after a delay of 1000 ms. Stimulus duration was 1200 ms, and the interval between the stimuli when the empty grid remained visible was 1000 ms. The items appeared in a fixed pseudo-randomized order. The task started with two items, and the sequence length was increased by one if at least three out of six sequences (50%) were remembered correctly. The task was terminated at the end of a specific span length if more than three out of six sequences were incorrectly recalled. Instructions and practice trials were repeated maximally twice if more than one error was made during practice. The total number of correctly recalled sequences across sequence lengths was used as a dependent variable for visual-spatial working memory.

2.4. Data analysis

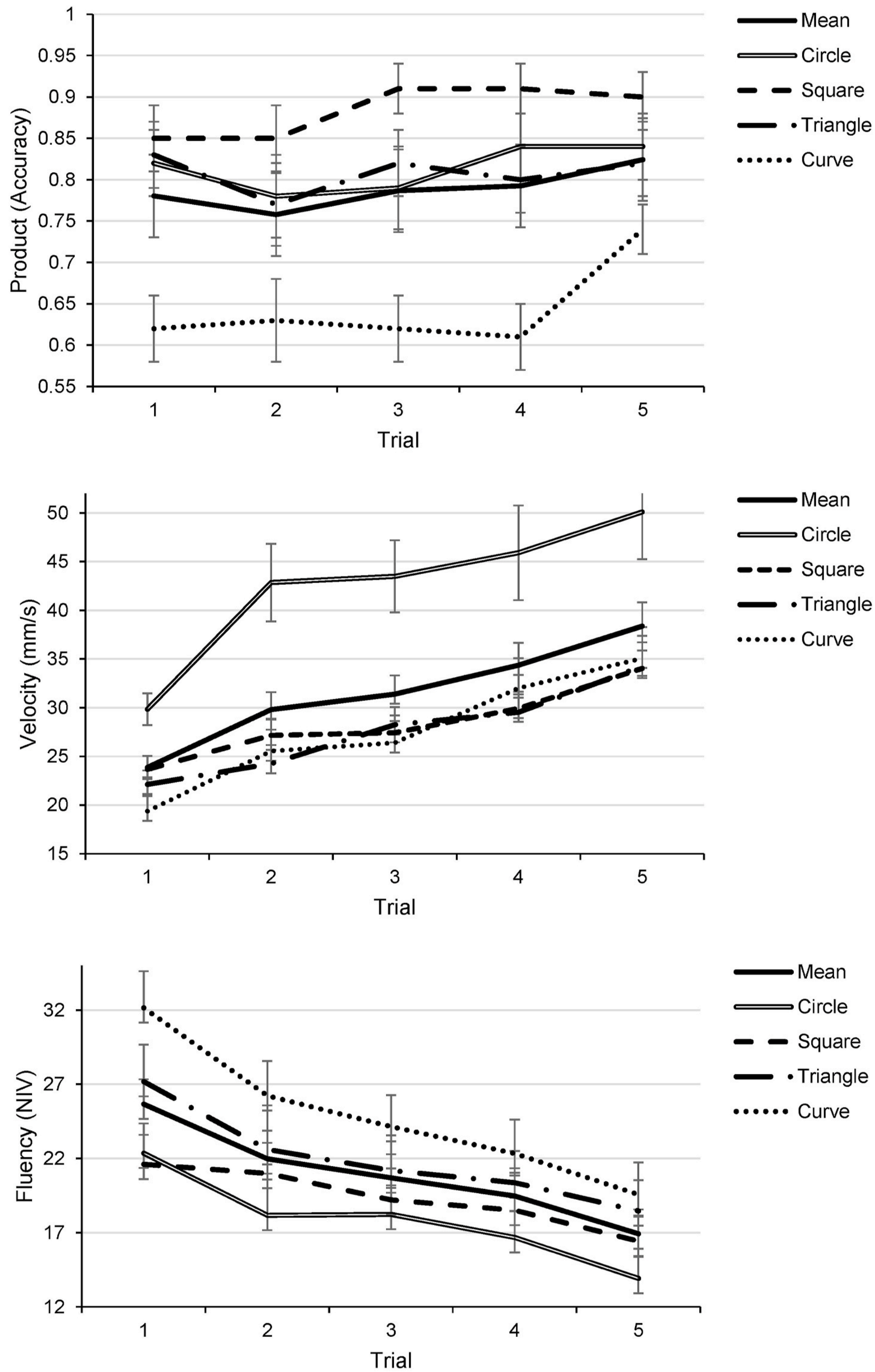
Data were analysed using IBM SPSS Statistics 25. A Multivariate Analysis of Variance (MANOVA) was calculated to investigate motor learning across five trials on different measures of VMI. Furthermore, a Multivariate Analysis of Covariance (MANCOVA) was calculated to explore the contribution of age, manual dexterity, and EF to different measures of VMI. Partial eta-squared as an estimate of effect size (η^2) is reported, with small effects defined as 0.01, a medium effect as 0.06, and a large effect as 0.14 (Cohen, 1988). Associations between measures were analysed using bivariate correlations. Differences between two correlations were tested with a Fisher Z-test (Lee & Preacher, 2013). An alpha level of 0.05 was used for assessing statistical significance.

Reaction times below 150 ms on the Hearts and Flowers task's trial-level were excluded for being too fast to be in response to the stimuli. Furthermore, scores exceeding three standard deviations (*SD*) of the inter-individual mean were defined as outliers and replaced with the third *SD* value. Overall, this was applied to 1.1% of all data points.

3. Results

3.1. Motor learning

This study aimed to explore early motor learning across five trials on the product and on process-based measures of copying shapes (i.e., VMI). The mean performance was calculated for each shape and each trial separately. We calculated a MANOVA with trial as independent, and accuracy, velocity, and fluency as dependent variables. Fig. 2 depicts motor learning on the product (i.e., accuracy; top panel) and process-based measures, namely velocity (middle panel) and fluency (bottom panel) for each shape as well as for the mean across the four shapes. There was no significant effect of trial on VMI accuracy, $F(4,1048) = 1.15$, $p = .33$, partial $\eta^2 = 0.00$. That is, despite a descriptive trend across five trials, the improvement was not statistically reliable. However, results revealed a significant effect of trial on velocity, $F(4,1048) = 15.51$, $p < .001$, partial $\eta^2 = 0.06$, and a significant effect of trial on fluency, $F(4,1048) = 8.74$, $p < .001$, partial $\eta^2 = 0.03$, indicating significant increases in velocity and fluency across the five trials. Eta-squared effect sizes indicate medium to large effects (Cohen, 1988).



Note. Motor learning across five trials on Different Shapes of the Copy Design task accuracy (top), fluency (middle) and velocity (bottom). Error bars represent standard errors of the mean.

Fig. 2. Motor learning on different measures of the Copy Design task
Note. Motor learning across five trials on different shapes of the Copy Design task accuracy (top), fluency (middle) and velocity (bottom). Error bars represent standard errors of the mean.

3.2. EF

Descriptive statistics for the EF tasks are presented in Table 1. Bivariate correlations between reaction times and accuracy measures of the Hearts and Flowers task revealed no substantial speed–accuracy trade-off for inhibition ($r = -0.23$, $p > .05$). For shifting, though, a significant speed–accuracy trade-off was found ($r = 0.30$, $p < .05$), with slower reaction times associated with higher accuracy. Not surprisingly, performance on inhibition and shifting was interrelated as well as performance on the two working memory tasks (see Appendix).

Table 1
Descriptive statistics of the EF measures (N = 54).

	M	*SD*	Range
Flowers block (inhibition; ms)	1052.18	316.92	614–2075
Flowers block (inhibition; accuracy)	.92	.09	.55–1
Mixed block (shifting; ms)	1344.64	299.92	796–2228
Mixed block (shifting; accuracy)	.86	.15	.28–1
Backwards color recall (sequences)	9.17	3.97	0–18
Position span (sequences)	5.37	3.37	0–16

Notes. M = Mean; *SD* = Standard deviation.

3.3. Associations between manual dexterity, EF, and VMI

To approach the second aim, which was to explore manual dexterity and EF contributions to different VMI measures, we aimed to broadly map EF and manual dexterity. Therefore, we used a composite EF score combining (i.e., summing) standardized performance in the four EF measures. Similarly, we combined (i.e., summed) standardized performance in the three manual dexterity tasks, with higher values indicating superior performance. As a first step, we calculated Pearson correlations between the included constructs. Pearson correlations revealed significant associations between EF and VMI accuracy (r = .27, $p < .001$), between EF and VMI fluency (r = 0.15, $p < .001$), and between EF and manual dexterity (r = 0.42, $p < .001$), indicating small to medium effects (Cohen, 1988). Further significant associations were found between manual dexterity and VMI accuracy (r = 0.28, $p < .001$), and manual dexterity and VMI fluency (r = 0.14, $p < .001$), indicating small effects (Cohen, 1988). The two VMI measures, accuracy and fluency, were correlated (r = 0.08, $p = .013$), indicating that higher accuracy is generally associated with a higher NIV, that is, lower fluency. However, the effect size indicates a negligible effect (Cohen, 1988). We did not include VMI velocity because VMI fluency already contains velocity components (fluency represents the number of inversions of velocity, NIV).

As a next step, a MANCOVA was calculated with VMI product and VMI fluency as dependent variables, trial as fixed factor, and age, manual dexterity, and EF as covariates. Results revealed significant effects of age on both VMI accuracy F (1,1046) = 8.77, $p = .003$, partial $\eta^2 = 0.01$, 1 – β = 0.84, and VMI fluency F (1,1046) = 7.93, $p = .005$, partial $\eta^2 = 0.01$, 1 – β = 0.80. Furthermore, significant effects of EF were found on both VMI accuracy F (1,1046) = 31.82, $p < .001$, partial $\eta^2 = 0.03$, 1 – β = 1.00, and VMI fluency F (1,1046) = 10.56, $p = .001$, partial $\eta^2 = 0.01$, 1 – β = 0.90. With regard to manual dexterity, significant effects of manual dexterity were found on both VMI accuracy F (1,1046) = 21.86, $p < .001$, partial $\eta^2 = 0.020$, 1 – β = 1.00, and VMI fluency F (1,1046) = 5.44, $p = .02$, partial $\eta^2 = 0.005$, 1 – β = 0.64. Eta-squared effect sizes indicate small effects (Cohen, 1988).

3.4. The VMI–EF link

The third aim of the study was to investigate the relationship between product and process-based measures of VMI and EF, respectively. As EF are expected to be especially involved when a task is new, Pearson correlations between VMI and EF were tested separately for trial one, when the Copy Design task was new, and trial five. As shown in Table 2, VMI accuracy in trial one was consistently associated with all EF measures, with correlation coefficients ranging from 0.32 to 0.42. In trial five, only the visual-spatial working memory, but no other EF task, correlated significantly with the VMI accuracy. Fisher's Z-test revealed a significant stronger association between VMI accuracy and shifting in trial one (r = 0.42) than trial five (r = 0.16), z = 2.18, $p = .029$. However, neither for inhibition (z = 1.18, $p = .24$), nor the working memory tasks (z = 0.90, $p = .37$ for the Backwards Colour Recall task; z = 0.23, $p = .82$ for the Position Span task), correlations with the VMI accuracy differed significantly for trial one and five.

We further explored how VMI fluency in trial one and five were correlated with each single EF task. The results revealed that fluency in trial one, but not in trial five, was associated with shifting and visual-spatial working memory. Positive correlations indicate that lower fluency was generally associated with superior EF. Correlation coefficients between fluency in trial one and five and EF did not differ, neither for shifting (z = 0.13, $p = .90$), nor visual-spatial working memory (z = 0.95, $p = .34$).

Table 2
Pearson correlations between VMI and EF, separate for trial one and five (N = 54).

Measure		Flowers block	Mixed block	Color recall	Position span
VMI product (raw scores)	Trial one	.36**	.42**	.34*	.32*
	Trial five	.21	.16	.23	.29*
VMI fluency (NIV)	Trial one	.24	.27*	-.02	.29*
	Trial five	.13	.26	-.02	.19

Note. NIV = Number of inversions of velocity. Z-standardized scores of the first trials on the circle, square, triangle, and curve were combined to calculate correlations. Z-standardized scores of the fifth trials were combined correspondingly.
*$p < .05$; **$p < .01$.

4. Discussion

This study examined 5- to 6-year-old children's early motor learning across five consecutive trials on copying geometric shapes. Over and above the traditionally used accuracy score of copying, we investigated processes that lead to a certain copy, specifically velocity and fluency. Secondly, the associations of manual dexterity, EF, VMI accuracy, and VMI fluency were investigated. Thirdly, the VMI–EF link was explored in the first trial of copying, when the task was new, and in the fifth trial.

Concerning our first aim, findings of motor learning on copying shapes revealed that children generally did not improve in terms of accuracy of copying across five trials. Likely, five practice trials did not suffice to statistically improve accuracy in this complex paper-and-pencil task, which is relatively new for children at this age. In contrast, findings on VMI processes revealed marked performance changes in terms of quicker and more fluent copying across the five trials. To copy a shape quicker and more fluently while maintaining accuracy indicates a performance improvement, considering the trade–off between speed and legibility. It seems that already after minimal practice, first adaptations to the task had been made. These adaptations may include more efficient planning of the finger movements, more precise hand–eye coordination, adjusting the in-hand manipulation of the pen as well as selecting and adapting task strategy. Furthermore, quicker and more fluent drawing points towards more mature drawing movements, which are related to early handwriting (Weil & Amundson, 1994). Although legibility, which refers to the accuracy of copying a letter or shape, is often considered more important than speed, performance speed is a key characteristic of handwriting quality (Dinehart, 2015) and is crucial to cope with classroom demands (Feder & Majnemer, 2007).

Comparable to the present findings, a recent investigation on motor learning using a mirror star-tracing task revealed an improvement in time to task completion, but no improvement in accuracy, measured immediately and 24 h after motor practice (Bootsma et al., 2018). Similarly, 5- to 8-year-old children's performance in the Invented Letter Task improved from initial training to the end of training in terms of performance speed; however, accuracy (i.e., error scores) was maintained (Julius et al., 2016). As the above-mentioned findings and those of the present study suggest, practice in paper-and-pencil tasks may first emerge in quicker performance before improvements in accuracy can be detected. It is not surprising that five repetitions of copying a shape did not suffice to improve the copy's accuracy meaningfully. Also handwriting needs to be taught and practiced intensively during primary school years and beyond before children's handwriting is considered automatized (Berninger & Graham, 1998).

Analyses on the interrelations of manual dexterity, EF, VMI accuracy, and VMI fluency taught us more about the construct VMI and the processes involved and required for copying shapes. As expected, and in line with previous studies (e.g., Pitchford et al., 2016), VMI accuracy and manual dexterity were interrelated in the present sample. This indicates that children with superior manual dexterity skills as measured with the Connecting Dots, Threading Beads, and Pegboard tasks, generally copied the shapes more accurately, and vice versa. Moreover, and was expected based on previous findings (Carlson et al., 2013; Pitchford et al., 2016), children's performance on VMI accuracy and EF were interrelated in the present sample. Children with high (compared to low) EF skills generally copied the shapes more accurately (and vice versa), likely because EF skills facilitate on-line adaptations of drawing and planning of further movements. To successfully copy a geometric shape, a child needs to build, maintain, and retrieve a spatial representation of the to-be copied shape. Besides, a child faces the challenge to cope with the complex manipulation of pen and paper, to adjust speed, strategy, and planning of finger movements – with all these processes involving EF.

Moreover, the present study revealed new insights into VMI by investigating fluency of copying and the link to EF and manual dexterity. The results showed that besides VMI accuracy, also fluency of copying is related to EF and manual dexterity. That is, the more often a child changed the velocity during copying, the better the child performed in the EF tasks, and vice versa. From a developmental perspective, children at this age are about to learn to copy shapes accurately (Beery et al., 2010). The drawing movements are not yet automated but need to be corrected and adapted continuously, which requires EF. These corrections and adaptations required to copy the shapes accurately are indicated by the positive (although weak) correlation between VMI accuracy and VMI fluency. Furthermore, not only VMI accuracy, but also VMI fluency was found to involve and require both manual dexterity skills and EF. However, the weak association between VMI accuracy and VMI fluency indicates that those two measures overlap only slightly and rather capture two different aspects of VMI. Low fluency in children at this age not only seems to foster higher accuracy, but also to go along with higher EF. While automated handwriting is characterized by high accuracy and high fluency (Dinehart, 2015), further studies need to shed light on the developmental trajectories and interactions of VMI accuracy and fluency across development.

This study further attempted to explore the VMI–EF link for both VMI accuracy and VMI fluency. As EF are assumed to be especially involved when a task is new, the VMI–EF link was expected to be stronger in the first trial of copying than in the fifth trial. In line with our hypothesis, results for VMI accuracy revealed significant correlations between performance in the first trial of VMI and the EF tasks. However, in the fifth trial, the accuracy was only related to one of the four EF measures, namely the Position Span task. These findings not only suggest that children who copied the shapes more accurately in trial one generally also performed better in the EF tasks and vice versa, but also indicate a strong involvement of EF during initial copying. It is likely that during initial copying, EF were especially required to plan and control finger movements, to adjust performance based on visual and proprioceptive feedback flexibly, and to adapt velocity to maintain or improve accuracy concurrently. This is in line with previous studies claiming that EF are especially required when a task is new and complex (Diamond, 2000; Maurer & Roebers, 2019). In contrast, when the shapes were copied the fifth time, EF's contribution likely faded into the background as the task and processes involved probably became more internalized, more practiced, and required less attention.

Translated to exercise and sport psychology, the results suggest a critical EF involvement at the beginning of learning a motor task and a relatively fast decline of EF involvement with ongoing practice. Similar findings were reported in the field of sport psychology, indicating high cognitive involvement in the early stages of motor learning followed by a decline (e.g., Furley & Memmert, 2010). The more automatized a movement is, the more cognitive resources are freed, which can be devoted to following more complex task instructions, implementing the instructor's feedback, or reacting flexibly to perturbations in the environment. A decline of EF involvement in the course of motor learning is also in line with neuroimaging data indicating decreasing neural activation with practice, especially in the prefrontal and premotor cortex (for an overview, see Lohse et al., 2014). However, we should consider that the learning curve and the cognitive involvement in a motor task may vary substantially depending on the task's difficulty and the learner's skill level (Ackerman, 1988).

To the best of our knowledge, this is the first study that investigated – over and above the product – also process-based measures of VMI, namely velocity and fluency, in early phases of motor learning on copying shapes and explored their relations to EF. Results indicate that in the present sample, children's fluency of copying shapes was positively, but only weakly related to shifting and visual-spatial working memory in the first trial, but not in the fifth trial. Positive correlations indicate that higher performance in shifting and visual-spatial working memory was associated with lower fluency. This finding may suggest that children who showed better shifting and visual-spatial working memory performance might have adjusted their drawing movements more often and, therefore, might have shown lower fluency. The ability to flexibly shift between different shapes and one's drawing and maintain the specific shapes more accurately in working memory was probably better developed in children with higher EF, leading to more frequent adaptations and a lower fluency of copying in those children.

Together, the present findings reveal unique and new insights into VMI and its underlying processes in preschool children. Copying shapes is a complex task for preschool children, requiring EF especially when the task is new. The results indicate that besides the accuracy of the copy, also fluency of copying is a crucial indicator of VMI, which is related to EF and manual dexterity, and has been widely neglected in the past. In future work, process-based perspectives on children's drawing and handwriting may offer more innovative insights not only into VMI, but also more generally into the motor–cognition link.

What limits the discussion of this study's findings is that accuracy on the Copy Design task did not meaningfully improve across five trials despite a trend. Consequently, increasingly accurate copying alone may not explain why the VMI–EF link tended to become weaker with increasing practice in copying shapes. Besides fluency, further VMI processes (e.g., number of pen lifts) and in-hand manipulation (e.g., pen grip, applied force) should be investigated in future studies, which will further our understanding of the development of legible and fluent copying and the specific motor and cognitive processes involved.

CRediT authorship contribution statement

Michelle N. Maurer: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Claudia M. Roebers:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix. Pearson correlations among the included variables (including age) below the diagonal; partial correlations controlling for age above the diagonal (N = 54)

Measures	1	2	3	4	5	6	7	8	9	10	11	Age
1 VMI accuracy trial 1	–	.49**	.31*	.22	-.11	-.14	.16	.45**	.45**	.25	.10	.43**
2 VMI accuracy trial 5	.57**	–	.31*	.18	-.30*	-.34*	.27	.25	.15	.15	.12	.35*
3 VMI fluency trial 1	.37**	.37**	–	.73**	-.17	-.33*	.13	.23	.26	-.05	.24	.24
4 VMI fluency trial 5	.19	.18	.68**	–	-.10	-.23	-.05	.18	.29*	.01	.18	.04
5 Threading Beads	-.20	-.36**	-.21	-.13	–	.50**	-.25	-.48**	-.33	.01	.19	-.29*
6 Pegboard	-.29*	-.42**	-.35*	-.27*	.55**	–	-.32*	-.27	-.31*	.01	.19	-.29*
7 Connecting Dots	.40**	.41**	.21	.02	-.34*	-.48**	–	.19	.24	.44**	.24	.44**
8 Inhibition	.36**	.21	.22	.16	-.46**	-.20	.10	–	.50**	.11	.05	.01
9 Shifting	.42**	.16	.26	.29*	-.33*	-.31*	.23	.48**	–	.14	.17	.05
10 Verbal working memory	.34*	.23	.02	-.01	-.04	-.06	.47**	.09	.16	–	.38**	.23
11 Visual-spatial working memory	.32*	.29*	.32*	.18	-.03*	-.04	.43**	.04	.17	.43**	–	.54**

Note. *$p < .05$; **$p < .01$.

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