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The longitudinal contribution of working memory and visuomotor integration to early and developing handwriting fluency

Lidia Truxius [a,b,*], Michelle N. Maurer [c,d], Judith Sägesser Wyss [c], Claudia M. Roebers [b]

[a] Institute for Research, Development, and Evaluation, University of Teacher Education Bern, Switzerland
[b] Institute of Psychology, University of Bern, Switzerland
[c] Institute for Special Needs Education, University of Teacher Education Bern, Switzerland
[d] Norwegian Reading Centre, University of Stavanger, Norway

A R T I C L E I N F O

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A B S T R A C T

Acquiring fluent handwriting in the first school years is crucial for academic achievement as attentional resources become available for more complex tasks. Yet, the role of cognitive and motor processes in developing handwriting fluency (as opposed to handwriting products) remains unclear. Therefore, this study investigated the longitudinal effects of working memory and visuomotor integration on handwriting fluency (number of inversions in velocity, pen stops, and pen lifts) in 364 children in their first year of handwriting tuition (M_{age} = 7.0 years) at three measurement points. We used cross-lagged structural equation models. Results revealed that handwriting fluency becomes independent of working memory early in development. Further, handwriting fluency predicted visuomotor integration skills, while visuomotor integration did not predict handwriting fluency. These findings imply that handwriting becomes independent early, and yields benefits for visuomotor integration, highlighting the relevance of early handwriting practice.

Educational relevance statement: In our study on early handwriting development, we found that a child's previous handwriting fluency (i.e., pen movement fluency) strongly predicts their current handwriting fluency. While factors like working memory and visuomotor integration are linked to handwriting fluency, they do not necessarily contribute to its improvement over time. This highlights the importance of consistent handwriting practice and educational interventions to enhance handwriting fluency at the beginning of school. Moreover, fostering handwriting fluency can also potentially payback for developing fundamental motor skills (i.e., visuomotor integration).

1. Introduction

Despite the discussion surrounding the increasing digitalization of schools and the growing importance of keyboarding, forming letters by hand remains crucial for beginning writers. Handwriting practice helps children to memorize and internalize letter shapes (Longcamp et al., 2005), activates the reading circuit, and might, therefore, enhance reading abilities (James & Engelhardt, 2012). It is especially important for beginning writers to automate writing movements, as this reduces their reliance on cognitive resources (i.e., working memory). The cognitive capacities that are freed up may facilitate learning in other school subjects such as math, reading, and literacy (Dinehart & Manfra, 2013; Suggate et al., 2018; Wicki et al., 2014).

Early handwriting is a complex skill requiring both language processing (e.g., an understanding of letter shapes, their sound correspondence, and spelling) and motor skills to control pen movements to produce fluent movements and a legible output. Handwriting is highly visually and cognitively demanding, especially at the beginning, and is therefore controlled, resulting in dysfluent movements (Fears & Lockman, 2018; Fitjar et al., 2021). At the beginning of handwriting instruction, children often begin by copying letters and words, which requires several skills working together. To illustrate, children must visually process the letter shape, perhaps name it, and activate an internal representation of the movement. They then hold the letter shape and correct movement in mind while coordinating their finger movements to form each stroke on paper. They visually monitor their work as they write, adjusting their movements to produce an accurate result.

The underlying mechanisms engaged in linguistic and spelling

* Corresponding author at: Institute of Psychology, University of Bern, Fabrikstrasse 8, 3012 Bern, Switzerland.
E-mail address: lidia.truxius@unibe.ch (L. Truxius).

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factors of writing as well as handwriting legibility – characteristics of the handwriting *product* – are relatively well investigated (Bourke et al., 2014; Cameron et al., 2015; Hooper et al., 2011; Weintraub & Graham, 2000). This body of literature shows that gender, vocabulary, fine motor coordination, and attention are crucial for legible handwriting development (Downing & Caravolas, 2023; Duiser et al., 2014; Kim & Park, 2019). Despite recognizing automaticity and handwriting fluency as crucial aspects of writing instruction, schools often struggle to provide effective learning opportunities and instruction to help children achieve fluent execution of handwriting – the handwriting *process* (Malpique et al., 2017; Medwell & Wray, 2007). While much is known about handwriting products and the factors influencing them, there is still limited understanding of the development of the handwriting *process (*i. e., handwriting fluency*)* and the role of the involved motor and cognitive processes when acquiring early handwriting skills. Therefore, the present study addresses this gap by exploring the longitudinal development of handwriting fluency, focusing on working memory and visuomotor integration as assumed interrelated mechanisms in beginning writers. This will be done by applying an interdependent perspective (cross-lagged modeling exploring one- and bi-directional influences).

1.1. Theoretical background

Previous theoretical models emphasize the importance of automatizing lower-level writing skills, such as handwriting and spelling, because these processes consume cognitive resources in working memory. Only when these skills become automatic cognitive capacities become freed for higher-level tasks such as text generation (Berninger & Winn, 2006; Kellogg, 1996). While these models are widely used to explain why handwriting automaticity and fluency are crucial for writing achievement (Salas & Silvente, 2020; Wicki et al., 2014), they do not explain the mechanisms beyond the development of lower-level processes (i.e., handwriting).

In contrast, van Galen (1991) conceptualized handwriting as a multicomponent task involving hierarchically structured cognitive, psychomotor, and biophysical processes. Writing begins with ideation (activating intentions) and progresses down to muscular adjustments (forming strokes), with each stroke reflecting the combined output of multiple higher-level processes. Although each higher-level processing module provides input for the next lower-level processing module, these processes operate concurrently rather than sequentially. This parallel processing requires temporary storage of information in a buffer, proposed as working memory. Van Galen's multicomponent approach highlights the interplay of parallel writing processes that all rely on cognitive capacities and affect handwriting fluency. In beginning writers who have not yet internalized letter forms and start by copying letters, visual, motor, and cognitive processes might most likely be involved.

The intertwining of handwriting fluency with cognitive, motor, and visual mechanisms becomes evident when young children are asked to produce unfamiliar words or challenging letters. They then typically slow down their writing, pause more frequently, and lift their pens more often (Danna et al., 2022; Fears & Lockman, 2018; Kandel & Perret, 2015). Eye-tracking studies have also shown increased visual fixations leading to changes in pen movements when children encounter unfamiliar letters (Fears & Lockman, 2018; Maldarelli et al., 2015). These findings highlight the close interdependency of executing handwriting by controlling pen movements (i.e., handwriting fluency) with cognitive and visual mechanisms, supporting the multicomponent perspective proposed by van Galens' handwriting theory (1991).

Furthermore, the multicomponent perspective has repeatedly been confirmed for handwriting products, emphasizing the critical role of cognitive abilities and motor skills for early writing development (for a review, see Achymy et al., 2022). Given that handwriting fluency and handwriting products are positively related (Fitjar et al., 2022; Maurer, 2023; Salas & Silvente, 2020), cognitive, visual, and motor factors may also influence handwriting fluency. However, while handwriting fluency and products are interrelated, they exhibit different developmental trajectories. Characteristics of handwriting fluency, such as speed, increase over the primary school years, whereas handwriting products, such as legibility, increase until second grade and plateau around third grade (Karlsdottir & Stefansson, 2002; Overvelde & Hulstijn, 2011). Furthermore, differential aspects predict handwriting fluency and products in more proficient writers (children in grades three to five). While graphomotor skills (i.e., fine motor and visuomotor skills) are more predictive for handwriting legibility, spelling is more important for handwriting fluency (Downing & Caravolas, 2023). However, it remains elusive what cognitive and motor mechanisms underlie the early stages of handwriting fluency, both concurrently and longitudinally.

1.2. Cognitive and motor mechanisms

In terms of assumed cognitive mechanisms, central theories of writing highlight the importance of working memory for higher-level writing (Berninger & Winn, 2006; Hayes, 1996; Olive, 2014), and van Galen (1991) suggests a storage buffer that is involved at all levels of writing. In line with this, working memory, which represents the ability to store and manipulate a limited amount of verbal and visual-spatial information in mind, is integral in managing handwriting demands. Verbal working memory processes linguistic information, such as letter sequences. In contrast, visual working memory handles images and spatial patterns necessary for forming letters. Around school entry, the two working memory components become more closely related and integrated, aligning into an overarching working memory factor (Gathercole et al., 2004). At this stage, children's working memory performance (i.e., accuracy) improves markedly, partly due to brain maturation and partly as an adaptation to the increasing cognitive demands of school entry (Davidson et al., 2023; Roberts et al., 2015).

Given that working memory is "our central mental workspace" it is not surprising that several studies have shown that higher working memory capacity is associated with better spelling and text generation skills (Berninger et al., 2010; Bourke et al., 2014; Valcan et al., 2020). Furthermore, working memory indirectly influences writing outcomes (i.e., orthography, text generation) through handwriting fluency, suggesting that working memory may also be important for the early development of handwriting fluency (Salas & Silvente, 2020; Wicki et al., 2014). These findings are also consistent with van Galen's (1991) multicomponent framework, in which working memory plays a crucial role in managing these simultaneous demands. This supports the assumption that children with better working memory capacity are better able to coordinate parallel processing, resulting in more fluent handwriting, both concurrently and longitudinally.

From a motor perspective, research on pen movement fluency suggests that visual and motor processing plays a crucial role in beginning handwriting and might function as a process module resulting in less fluent handwriting (Fears & Lockman, 2018; Maldarelli et al., 2015). Furthermore, children in the classroom are frequently instructed to copy letters and words to internalize movement sequences and letter shapes, indicating the importance of motor mechanisms. When copying letters and words, children process and maintain visual information and translate the information into motor movements. This complex skill is known as visuomotor integration (VMI). Typically measured using copy-design tasks, VMI develops fast across the kindergarten years (age four to five years) and stabilizes around school entry (Brock et al., 2018; Fang et al., 2017). VMI is well investigated in the context of handwriting products in terms of legibility and writing quality. Individual differences in VMI are associated with higher handwriting quality (Bara & Gentaz, 2011; Daly et al., 2003; Kaiser et al., 2009) and may be impaired in children with handwriting difficulties (Volman et al., 2006; Weintraub & Graham, 2000).

Beyond motor and visual aspects, VMI also entails cognitive demands, as the visual information must be represented in the mind while coordinating motor movements (Cameron et al., 2015). It is therefore not surprising that VMI is considered, together with other cognitive concepts such as working memory, an important school readiness indicator relevant for the acquisition of math and reading at school entry (Becker et al., 2014; Cameron et al., 2015). Furthermore, VMI and working memory contribute to the automation of motor skills (i.e., handwriting), freeing cognitive resources for more complex academic tasks (Diamond, 2000; Khatib et al., 2022; Maurer & Roebers, 2021; McClelland & Cameron, 2019).

Working memory and VMI co-develop in a bidirectional and synergistic manner (Cameron et al., 2012; Cameron et al., 2015; McClelland & Cameron, 2019). Improved memory and processing abilities (i.e., working memory) facilitate the processing of visual information, helping VMI to become more automatic, while enhanced VMI skills may reduce the cognitive demands on working memory as they become more automatic (Diamond, 2000; Maurer & Roebers, 2021; McClelland & Cameron, 2019). Despite their interdependence, these two constructs remain theoretically distinct and predict literacy achievement differentially (Becker et al., 2014; Khatib et al., 2022). This becomes also evident from previous research showing that these constructs play different roles in handwriting. VMI appears to be more critical for the production of legible handwriting (Bara & Gentaz, 2011; Daly et al., 2003; Downing & Caravolas, 2023), whereas working memory is more influential in the production of written products such as texts and spelling (Bourke et al., 2014; Cordeiro et al., 2020).

1.3. *Measurement of handwriting fluency*

In contrast to handwriting products, that focus on the result, the handwriting process provides insight into the execution and, therefore, fluency of pen movements. Digitized tablets allow the recording of temporal information on handwriting processes, which can be transformed into several kinematic aspects. These kinematic aspects provide information about the fluency of pen movements during handwriting, each highlighting different aspects of handwriting fluency, despite some overlap (Paz-Villagrán et al., 2014; Truxius et al., 2024). For example, the number of strokes per letter represents the smoothness of the pen movement and can be assessed by the number of velocity changes (number of inversions in velocity, NIV). Each stroke involves an acceleration and deceleration, with a change in velocity occurring between them. These changes in velocity indicate hesitation in writing movements. A larger number of strokes indicates more hesitation during writing and, therefore, less automatized movements. These hesitations are typically more frequent in beginning than proficient writers (Accardo et al., 2013; Rueckriegel et al., 2008).

Another well-established indicator of handwriting fluency is pausing. Pausing is, to some extent, a natural and necessary part of handwriting, but when they become excessively long or unstructured, they may also indicate handwriting difficulties (Pascual et al., 2023). There are typically two types of pauses – pen stops and pen lifts. A pen stop occurs when the pen is momentarily held still, usually to change direction or adjust the writing movement. For example, when writing the letter "V", a brief pause to change direction represents a necessary and integral interruption in the writing movement (Fitjar et al., 2022). However, when pen stops become excessively long, they may represent interruptions in the writing movements and signal difficulties in maintaining fluent and smooth movements. This is particularly evident in dysgraphic children, who exhibit longer pen stops than typically developing children (Paz-Villagrán et al., 2014). In contrast, a pen lift involves raising the pen off the paper to start a new letter stroke. For instance, lifting the pen to begin the second stroke of a "T" is an essential part of the handwriting process, reflecting a planned and controlled movement (Fitjar et al., 2022). Pen lifts indicate continuous writing movements and the planning involved in transitioning between strokes and letters. Since young children are less practiced in their writing movements and therefore take more planning time, they typically show longer pen lifts than adults. For the same reason, dysgraphic children tend to display longer pen lifts than same-age typically developing peers (Paz-Villagrán et al., 2014; Rosenblum et al., 2003).

Given that handwriting fluency is multifaceted, previous studies have used a latent construct to integrate multiple kinematic measures into a single, more comprehensive representation of handwriting fluency (Asselborn et al., 2018; Gargot et al., 2020; Truxius et al., 2024). A latent handwriting fluency measure reduces measurement error and allows a more robust assessment of fluency by weighing each measure according to its contribution. Longitudinally, this approach provides insights into how the importance of different fluency components evolves, allowing underlying developmental patterns to be more effectively captured.

1.4. *Present study*

Handwriting is a multi-component psychomotor task that requires the integration of several parallel cognitive and motor processes (van Galen, 1991). While working memory and VMI are important for automatizing motor movements (Diamond, 2000; Maurer & Roebers, 2021) and in developing handwriting products (Bourke et al., 2014; Cordeiro et al., 2020; Daly et al., 2003; Downing & Caravolas, 2023), few studies have investigated their role in handwriting fluency – a characteristic of the handwriting process. Recent cross-sectional research has produced mixed results. One study on beginning writers found a modest association between working memory and handwriting fluency but none with VMI (Truxius et al., 2024). Conversely, another study of slightly more proficient writers found relations between VMI, working memory, and handwriting fluency (Maurer, 2023). These findings suggest that VMI and working memory may play a role in developing handwriting fluency, and their interdependencies may change over time. Therefore, this study investigates longitudinal changes in handwriting fluency and the concurrent and cross-lagged effects of working memory and VMI across three measurement points in the first year of handwriting tuition.

Considering that children must process information from multiple levels of writing, such as integrating visual cues and motor movements while contending limited working memory capacity, and handwriting is not automated yet, we hypothesized that VMI and working memory would be involved in developing handwriting fluency. According to van Galen's (1991) model, improved working memory and VMI should enable children to handle the parallel processing demands of handwriting more effectively, resulting in more fluent handwriting concurrently and longitudinally.

When copying letters and symbols, VMI enables children to perceive visually, cognitively represent, and transform letters into controlled strokes. Therefore, we hypothesize that VMI correlates with and predicts handwriting fluency. Given that VMI shares variance with other cognitive skills (Becker et al., 2014; Cameron et al., 2015), VMI was expected to influence handwriting fluency in two ways. Directly, as better VMI allows children to refixate the stimuli less often, allowing them to visually control their pen movements more accurately and produce more fluent movements. Indirectly, as enhanced VMI skills may free up working memory capacity, further improving handwriting fluency. Working memory should independently be related and predictive to handwriting fluency by reducing cognitive load, allowing children to retain word information while coordinating strokes. In addition, we expect both skills to play a more important role early in handwriting, as handwriting movements become more automatized with practice and over time (Diamond, 2000; Maurer & Roebers, 2021). Given that interventions for VMI and working memory have been highly effective in kindergarten (Röthlisberger et al., 2012; Taverna et al., 2020; Zhang et al., 2018), these skills are likely to have reached a certain level of stability by school age. Consequently, we hypothesize that VMI and working memory will enhance handwriting fluency rather than being influenced by handwriting itself.

To account for shared and unique variances between VMI and working memory, we present the results of the cross-lagged findings in two steps. In the first step, we explored the longitudinal interactions of working memory and VMI on a handwriting fluency factor, respectively. In a second step, we concurrently included working memory and VMI into the model to test their *relative* importance for handwriting acquisition and control for shared variances in working memory and VMI. In accordance with previous findings in other school subjects (Becker et al., 2014; Cameron et al., 2015), we expected working memory and VMI to contribute equally to handwriting fluency when being entered concurrently.

2. Methods

2.1. Participants

The data for the analyses presented here are part of a larger research project in Switzerland investigating different handwriting interventions in beginning writers. In this contribution, we were interested in the development of children's handwriting fluency. Therefore, we focus here on the subsample that underwent no intervention. This subsample consists of $N = 364$ children (49 % girls) from 24 first-grade classes. The school classes were recruited from public schools in urban and rural areas. Formal handwriting instruction in Switzerland begins in first grade. In kindergarten, children engage in playful graphomotor activities, such as drawing and name writing but receive no explicit or formal instruction on letter shapes.

Children were tested at three measurement points with an interval of six months each (T1: in the second quarter of first grade, October – December 2021; T2: in the last quarter of first grade, April – June 2022; T3: at the second quarter of second grade, October – December 2022). Children's mean age at T1 was $M = 83.6$ months, $SD = 4.6$. All children had already developed a hand preference at the first measurement point, with 86 % being right-handed. For most children, the first language was Swiss German/German (74.5 %). However, all children had some basic skills of German as they attended school and handwriting instruction in this language. Prior to testing, we ensured all children understood the instructions.

2.2. Procedure

The study was approved by the Ethics Committee of the University of Teacher Education Bern (Approval No. 19s000201). Parents gave written consent for their children's participation. Trained research assistants tested the children within two school days. Children were tested in the whole class (VMI) and small groups, with children fulfilling the task individually on laptops (working memory) or individually in a one-to-one setting (handwriting). Each task was set up to take a maximum of twenty minutes to prevent fatigue.

2.3. Measures

2.3.1. Working memory

Two different span tasks were used to measure working memory. A Backward Color span task to measure verbal working memory and a Backward Position span task to measure visual-spatial working memory. Both tasks are well established to measure working memory capacities in young children (Roebers et al., 2014; Schmid et al., 2008; van der Ven et al., 2013) and were administered using a laptop computer with a touch screen and audio instructions.

The Backward Color span task (Roebers et al., 2011) is embedded in a cover story of a dwarf losing colored discs. Sequences of different colors appear on the screen, and children are instructed to select the correct colored discs out of a palette of six colors in reverse order. After four practice trials, the task starts with a block of six sequences of two discs each. After three correct sequences out of six within a block, the number of presented blocks increases by one disc. The task terminates after four or more incorrect sequences within a block (maximum five blocks with a span of six trials). For each child, we calculated the sum of correctly recalled trials, with possible scores ranging from a minimum of 0 to a maximum of 30 points.

For the Backward Position span task (Frick & Möhring, 2015), a mole appears in different fields in a 4 × 4 grid. Children are instructed to touch the fields where the mole appeared in reverse order. Like in the Color span task, the task starts after four practice trials with a block of six sequences of two stimuli each. The task continues with one additional appearance of the mole in a sequence when the child correctly answers three out of six sequences within a block. The task terminates after four or more incorrect sequences within a block (maximum five blocks with a span of six trials). Like in the Backward Color span task, we calculated the sum of correctly remembered trials ranging from a minimum of 0 to a maximum of 30 possible correct answers.

2.3.2. Visuomotor integration (VMI)

VMI was assessed using the GRAFOS Screening with its extension (Sägesser & Eckhart, 2016). The GRAFOS Screening is a standardized instrument to assess graphomotor skills (i.e., VMI and fine motor skills) in kindergarten to second-grade children. Similar to the well-established Beery VMI test (Beery et al., 2010), the GRAFOS Screening uses a copy-design task to measure the accuracy of the shape (i.e., characteristic of product). In two parts, children copy different shapes of varying difficulty, six times each. In contrast to Beery's VMI test, GRAFOS also controls fine motor movements, especially relevant for handwriting, as children copy the forms in small squares (1cm^2). The first part contains eight shapes fundamental to letter forms and letter writing (e.g., arches, lines, squares). The second part contains five more complex shapes that require more advanced visuomotor control (e.g., drops, connected loops). Construct validity is given as GRAFOS Screening is related to Beerys VMI test by $r = 0.70$ (Sägesser & Eckhart, 2016). Each copied shape was rated according to predefined criteria (0 = incorrect reproduction; 1 = partly correct reproduction; 2 = correct reproduction), and a mean score for fundamental shapes and complex shapes was calculated resulting in a minimum score of 0 and a maximum of 2. Research assistants rated children's VMI skills. We calculated the interrater reliability for each rater with an expert rater using a weighted Cohens' Kappa coefficient. The interrater reliability for different raters varied between $\kappa = 0.66$ and 0.78, indicating good agreement (Altman, 1991). Internal consistency (Cronbach α) was good and varied between the three measurement points between $\alpha = 0.82$ to 0.86 for fundamental shapes and $\alpha = 0.85$ to 0.86 for complex shapes.

2.3.3. Handwriting fluency

To measure handwriting fluency at each measurement, children copied the same set of words: four words of medium length (six letters) and two long words (eight letters) in manuscript style. They wrote with a special inking pen (WACOM Inking Pen®) on a piece of paper into light grey bars (height of 1 cm) to ensure all children wrote in a size that requires fine motor movements. The paper was placed on a digitized tablet (WACOM Intuos Pro®) connected to a computer using the software CSWin (Mai & Marquardt, 2016) to quantify kinematic variables of pen movements during writing. The software defines the accuracy of spatial resolution by 0.1 mm (x-axis and y-axis) and recording frequency by 200 Hz. For this study, we considered the following kinematic measures: number of inversions in velocity (NIV), duration of pen lifted from the writing surface, and duration of pen stops. The NIV is a measure of strokes and movement automaticity. It quantifies the changes in velocity, with more changes indicating more accelerations and decelerations, resulting in more strokes and, therefore, lower pen movement fluency. The velocity profiles are filtered before calculating the number of inversions using non-parametric regression methods and kernel estimates (Marquardt & Mai, 1994). Pen lifts are quantified in the time the pen is lifted from the writing surface (in ms), and pen stops are defined by an immobile pen on paper or in the air (> 200 ms), also in milliseconds. These measures target different aspects of handwriting fluency in young children (Fears & Lockman, 2018; Maldarelli et al., 2015; Paz-Villagrán et al., 2014). Their latent handwriting factor is related to teacher's rating of handwriting skills ($r = 0.11$; Truxius et al., 2024).

2.4. Data analyses

We applied structural equation models to design cross-lagged models using the software RStudio and the package Lavaan (Rosseel, 2012). Outliers were excluded case-wise (i.e., values exceeding three standard deviations from the sample's mean). The exclusions varied between zero cases (for working memory and VMI measures at all measurement points) and 12 cases (for pen stops at T2). We had missing data due to illness and accounted for missing data using full maximum likelihood estimation. All manifest measures were z-transformed before entering the model to receive identical metrics across tasks. We allowed the covariances between measures across measurement points to covary to account for shared variances. The model fit indices were evaluated based on criteria recommended by Hu and Bentler (1999). Good model fit is indicated by a CFI > 0.95, RMSEA <0.06, and SRMR <0.08.

3. Results

Table 1 shows the descriptives and repeated measures ANOVA for all the measures included in the structural equation model. The mean values of the three indicators of handwriting fluency all decreased significantly over time, indicating more fluent pen movements over time. The post-hoc tests revealed significant changes for all variables between T1 and T2 and between T2 and T3. For working memory and VMI, performance on all measures increased over time, and post-hoc tests showed significant changes for all working memory and VMI measures between T1 and T2, and between T2 and T3. A correlation matrix with all the reported variables is shown in the Appendix.

To investigate the longitudinal development of handwriting fluency and the involvement of working memory and VMI, we conducted several cross-lagged structural equation models. First, we computed structural equation models relating handwriting fluency to working memory (Fig. 1). In this model, handwriting fluency was explained to a similar extent by NIV, pen stops, and pen lifts at each measurement point. Even though pen stops explained slightly more variance to the handwriting fluency factor, all handwriting fluency measures loaded significantly on the latent handwriting factor, indicating a valid and reliable estimate. For working memory, verbal working memory loaded more strongly on the working memory factor than visual-spatial working memory. This was especially apparent at T1. Overall, the model fitted the data well: CFI = 0.97, RMSEA = 0.05, SRMR = 0.06. Handwriting fluency and working memory were slightly interrelated at the beginning of first grade (T1; $r = -0.25$). Considering the stability over time, both working memory and handwriting fluency showed high stabilities with slightly higher stabilities from the second to the third than from the first to the second measurement point. Most importantly, we found no significant cross-lagged paths indicating no longitudinal effects of working memory on handwriting or vice versa.

Fig. 2 shows the respective cross-lagged model for VMI and handwriting fluency. Again, handwriting fluency was explained to similar extents by NIV, pen stops, and pen lifts over time, similar to the working memory model (see Fig. 1). Even though both fundamental and complex shapes loaded significantly on the VMI factor across all measures, it is essential to note that when children became more proficient in VMI, factor loadings changed, with the complex shapes becoming more indicative of the latent VMI construct. Fit indices showed a moderate fit: CFI = 0.94, RMSEA = 0.08, SRMR = 0.08. There was a small but significant correlation between VMI and handwriting fluency at the beginning of first grade (T1; $r = -0.18$, $p = .03$). The stabilities were similar to the previous model including working memory. Handwriting fluency and VMI were relatively stable, with more stable effects between the second and third than the first and second measurement points. Contrary to our expectation, no cross-lagged paths were found from earlier VMI to later handwriting fluency. However, and most interestingly, there was a significant cross-lagged path from handwriting fluency at the beginning of first grade (T1) to VMI at the end of first grade (T2), indicating that early handwriting fluency supports later VMI skills.

As a last step, we simultaneously included working memory and VMI into the model to investigate their relative effects on handwriting fluency development (Fig. 3). The model showed a good fit: CFI = 0.95, RMSEA = 0.06, SRMR = 0.07. Handwriting fluency was related to working memory and VMI at the beginning of first grade. The stabilities were comparable to the models with only one predictor revealing high stabilities. When including working memory and VMI simultaneously, the cross-lagged effect of handwriting at the first measurement point on VMI on the second measurement point remained significant. No other substantial cross-lagged effects between handwriting fluency, working memory, and VMI emerged, indicating that working memory and VMI contributed independently to handwriting fluency development.

Table 1
Means of handwriting fluency, working memory, and visuomotor integration measures.

	Measurement						
	T1		T2		T3		
	M (*SD*)	Min / Max	*M* (*SD*)	Min / Max	*M* (*SD*)	Min / Max	*F* (df1, df2), *p*
Handwriting fluency measures							
NIV	8.96 (3.47)	2.42 / 20.34	5.59 (2.61)	1.30 / 15.02	4.31 (1.97)	1.25 / 11.67	301.33 (2295), $p < .001$
pen stops (ms)	5005.23 (3810.76)	130.83 / 17,127.83	1631.02 (1347.58)	36.17 / 6826.83	962.80 (909.36)	0 / 4736.17	730.38 (2303), $p < .001$
pen lifts (ms)	16,531.09 (5829.87)	2467.67 / 34,009.33	9351.78 (3703.20)	2215.67 / 21,560.00	6794.88 (2605.85)	1533.00 / 16,001.17	730.38 (2303), $p < .001$
working memory							
verbal working memory (number of correct trials)	6.81 (2.89)	0 / 15	7.62 (3.22)	0 / 17	8.12 (3.27)	0 / 17	26.68 (2329), $p < .001$
visual-spatial working memory (number of correct trials)	6.61 (3.61)	0 / 17	8.49 (3.67)	0 / 19	10.00 (3.58)	0 / 20	124.03 (2331), $p < .001$
visuomotor integration							
fundamental shapes	1.54 (0.19)	0.60 / 1.96	1.65 (0.16)	0.73 / 2.0	1.69 (0.16)	0.98 / 1.98	109.74 (2325), $p < .001$
complex shapes	0.81 (0.29)	0 / 1.67	1.03 (0.31)	0.13 / 1.8	1.05 (0.29)	0.10 / 1.8	184.79 (2324), $p < .001$

Note. NIV = numbers of inversions in velocity.

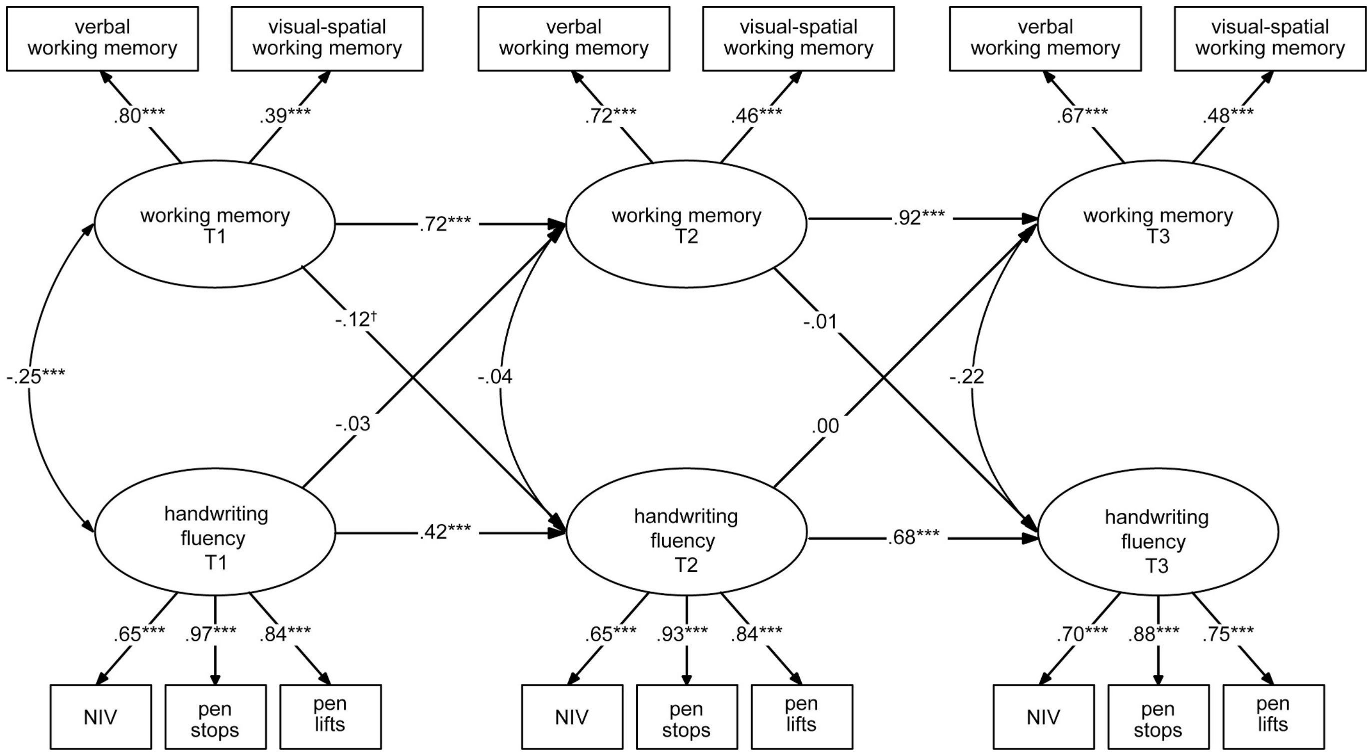

Fig. 1. Longitudinal associations for working memory and handwriting fluency.
Note. NIV = numbers of inversions in velocity. † $p = .08$, *** $p < .001$.

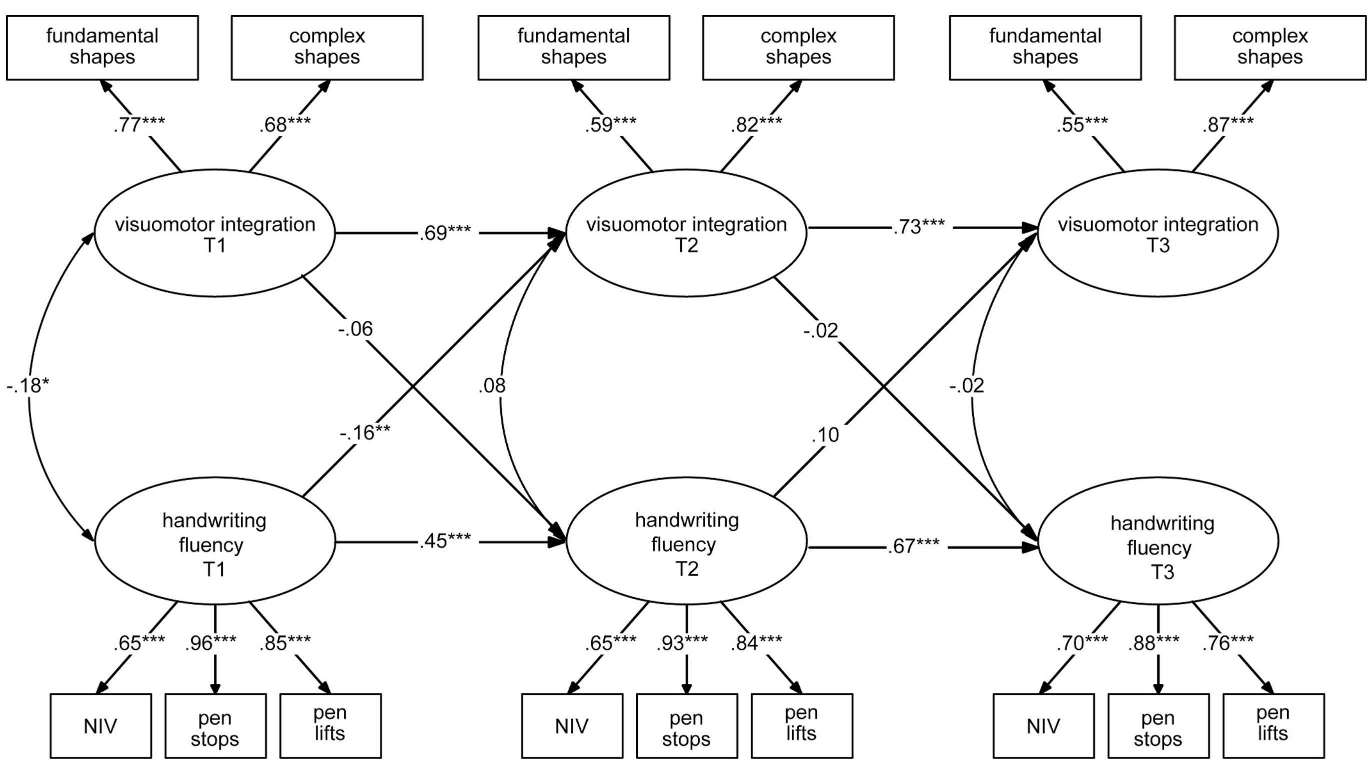

Fig. 2. Longitudinal associations for visuomotor integration and handwriting process.
Note. NIV = numbers of inversions in velocity. * $p < .05$, ** $p < .01$, *** $p < .001$.

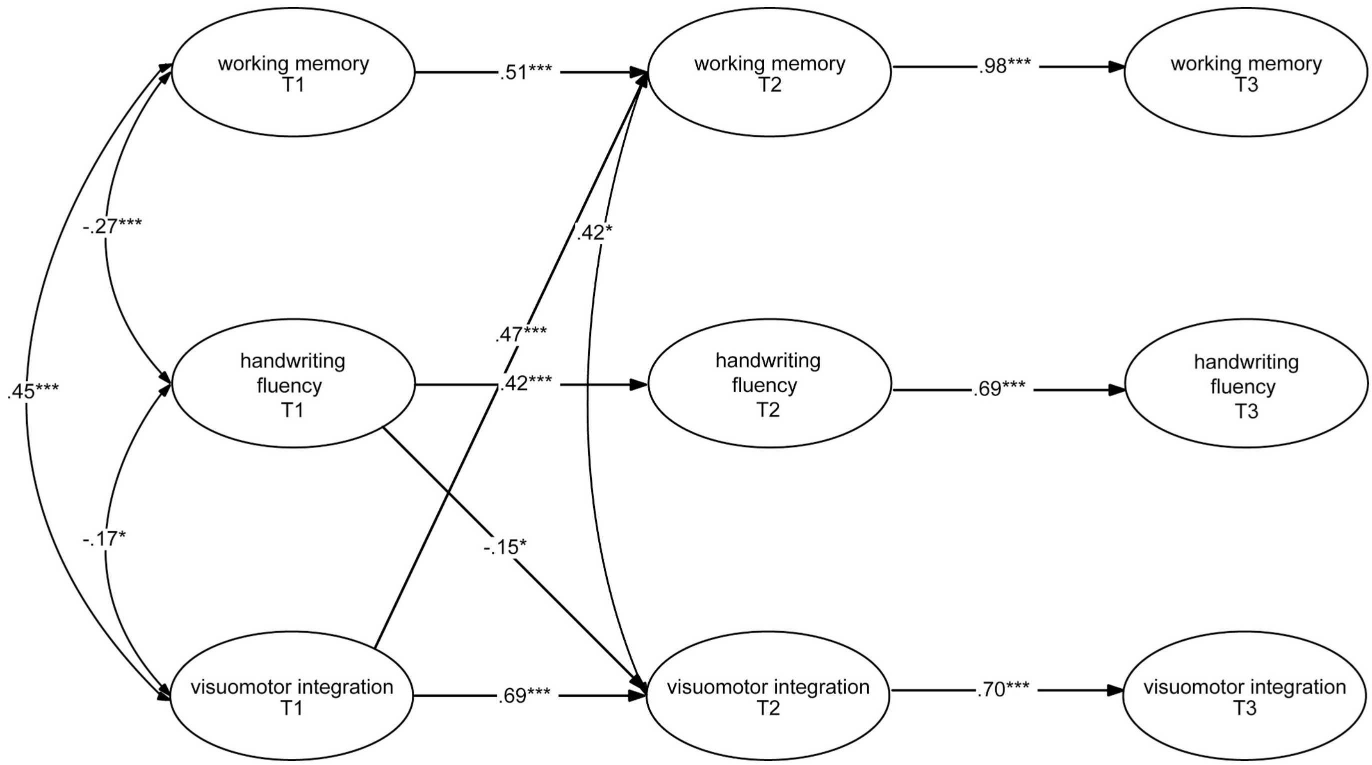

Fig. 3. Longitudinal associations for working memory, visuomotor integration, and handwriting process. *Note.* Only significant paths are shown in the model. * $p < .05$, ** $p < .01$, *** $p < .001$.

Furthermore, working memory and VMI were interrelated both at the beginning (T1; $r = 0.45$, $p < .001$) and at the end of first grade (T2; $r = 0.42$, $p = .02$) but no longer at the beginning of the second grade (T3). It appears that early VMI skills (T1) promote the development of working memory (T2).

4. Discussion

This study aimed to better understand the longitudinal relations between working memory, VMI, and handwriting fluency. While research on writing achievement has traditionally focused on product measures like legibility and text quality, our study addresses a critical gap in the literature by exploring how working memory and VMI—two well-established school-readiness indicators—contribute to the handwriting process (i.e., handwriting fluency), both cross-sectionally and longitudinally. Although kinematic measures of pen movements to measure handwriting fluency have become increasingly popular in recent years, the role of individual differences in working memory and VMI in developing handwriting fluency has remained unclear until now. To address this, we estimated several cross-lagged structural equation models across three measurement points, allowing us to estimate potential cross-sectional and longitudinal, one- and bi-directional effects of handwriting fluency, working memory, and VMI, respectively. We expected that working memory and VMI would support the development of handwriting fluency cross-sectionally and longitudinally, as better working memory and VMI would allow for appropriate engagement and practice of handwriting fluency. We found that—when considered separately—both working memory and VMI were significantly related to handwriting fluency and that the two variables also shared substantial amounts of common variances, underscoring how fundamentally interwoven these processes are, already early in development. However, working memory and VMI were only related to handwriting fluency at the beginning of handwriting acquisition (T1) but no longer when controlling for prior performance. Surprisingly, we found very high stabilities for all measures, especially for working memory and VMI, but also for handwriting fluency. No longitudinal effects of working memory and VMI on handwriting fluency emerged.

4.1. Developmental changes in working memory, VMI, and handwriting fluency

The results of the repeated measures ANOVA highlighted the overall improvement over the first school year for all measures, highlighting the sensitivity of our measures and underlining that this age range is a period of dynamic development. These findings are in line with other research suggesting improvement of handwriting fluency across primary school years (Karlsdottir & Stefansson, 2002; Overvelde & Hulstijn, 2011) and more accurate working memory processing with increasing schooling (Roberts et al., 2015), while VMI skills appear to improve only little around this time (Brock et al., 2018; Fang et al., 2017). Moreover, structural equation models revealed high stabilities for all constructs, indicating that prior performance in working memory, VMI, or handwriting fluency was the best predictor of later performance. These high stabilities suggest that individual differences in these skills have likely stabilized before children enter school and receive formal handwriting instruction. The substantial stability in the rank order of children implies that interventions for struggling children should be implemented as early as possible since stability defines the upper limits of any intervention's effect (Adachi & Willoughby, 2015). These findings are in line with previous research suggesting that working memory and VMI interventions are effective when applied in kindergarten settings (Röthlisberger et al., 2012; Taverna et al., 2020; Zhang et al., 2018). In the context of our main research questions, these high stabilities make it technically difficult and unlikely to identify additional factors that explain variances in handwriting process development. However, despite these high stabilities, we observed some correlational and bidirectional relations that we will discuss in the following paragraphs.

4.2. Interrelations between working memory, VMI, and handwriting fluency

At the beginning of handwriting acquisition, in the second quarter of the first school year, children's handwriting fluency was associated with working memory and VMI. However, with additional practice during the school year and when controlling for prior performance, handwriting fluency became statistically independent of these two early school readiness factors. This pattern of results was consistent in all models, also when controlling for shared variance between working memory and VMI. There was no longitudinal relationship over and above the cross-sectional links for working memory or visuomotor integration predicting handwriting fluency. These findings were surprising as we expected that working memory and VMI would contribute significantly to the development of handwriting fluency, as both are relevant for automatizing motor movements (Diamond, 2000; Maurer & Roebers, 2021) and other aspects of writing (Downing & Caravolas, 2023). Previous research investigating the effects of working memory on writing often focused on older samples and more complex aspects of writing, such as spelling and text generation (Kent et al., 2014; Salas & Silvente, 2020; Valcan et al., 2020). In contrast, this study concentrated on the execution of handwriting (i.e., handwriting fluency). Although previous studies have shown that children adapt their pen movements when the task becomes more complex cognitively or visually (Fears & Lockman, 2018; Kandel & Perret, 2015; Maldarelli et al., 2015), the skills required for producing orthographically correct written content may differ from those needed to execute handwriting during letter copying. These differences in task demand could explain why working memory and VMI did not predict handwriting fluency as strongly as expected.

Furthermore, our findings suggest that handwriting fluency measured by kinematic measures of pen movements differs from handwriting products measured by characteristics of quality, such as legibility. Even though these aspects of handwriting are associated (Fitjar et al., 2022; Maurer, 2023), they follow different developmental trajectories (Karlsdottir & Stefansson, 2002; Overvelde & Hulstijn, 2011) and might depend on different motor and cognitive aspects at different times in development. Recent findings by Downing and Caravolas (2023) suggest that handwriting legibility may depend more on graphomotor skills, while handwriting fluency may be more closely linked to spelling abilities. However, the interrelationship between handwriting fluency, legibility, and spelling remains unclear and should be addressed in future research.

For the bidirectional relations, we found two significant effects. First, contrary to our expectations, handwriting fluency at the first measurement point predicted VMI at the second measurement point at the end of first grade, indicating that handwriting fluency provides early learning opportunities for motor control and the ability to process visual information and produce forms accurately. We had not anticipated this effect due to the stability of VMI (Fang et al., 2017; Zhang et al., 2018). However, this finding is consistent with other school readiness studies, uncovering, for example, reciprocal relations between early math skills and fine motor and visuomotor development (Fuhs et al., 2014; Kim et al., 2018). Since VMI supports the development of math and reading abilities beyond handwriting, particularly through spatial reasoning and attention-related aspects (see Khatib et al., 2022), these findings suggest that early handwriting practice could bolster academic achievement both directly and indirectly. In other words, our findings and others argue against eliminating or reducing handwriting instruction and practice. However, to our knowledge, the longitudinal effects of the execution of handwriting (handwriting fluency) on academic achievement in other school subjects than literacy have not yet been investigated and could represent an interesting topic for future work.

Another bidirectional cross-lagged effect was found in the model that examined the unique variances of working memory and VMI on handwriting fluency. Although the structure and relations between working memory and VMI on handwriting fluency did not change when both were entered into the model simultaneously, we found a bidirectional effect from VMI in the first quarter of first grade on working memory at the end of first grade. These findings are consistent with previous studies showing the predictive power of VMI and motor skills on executive functions (Sulik et al., 2018; Zysset et al., 2018). A possible explanation for these findings could be that better VMI skills at school entry allow young children to explore written content and visual stimuli differently. Young children with better VMI might process visual information in cognitively less demanding units and have learned to identify the most important information for processing. Consequently, strategies that enhance their working memory processing improve.

4.3. Limitations and Strengths

Finally, some limitations need to be considered. The working memory and VMI indicators (manifest variables) loaded unequally across time, indicating different weighting of the aspects within the underlying constructs. Since we studied children just starting school in a phase associated with rapid development in motor and cognitive skills, we applied age-appropriate measures capturing children's fast development over time. Although the factor loadings varied over time, the stabilities were high, indicating reliable measures of the working memory and VMI construct over time.

The fact that we did not find longitudinal links of either working memory or VMI on later handwriting fluency was slightly surprising. We discuss two aspects here. First, our understanding of handwriting fluency (our measures) employed in this study, as well as their connections to effective writing outcomes, remains somewhat limited. While previous research has shown that letter knowledge and spelling abilities are related to handwriting fluency (Danna et al., 2022; Fears & Lockman, 2018; Fitjar et al., 2021) and that handwriting fluency differs between dysgraphic and typically developing children (Paz-Villagrán et al., 2014; Rosenblum et al., 2003), it remains unclear whether working memory and VMI measures directly contribute to better writing or if writing competencies manifest within handwriting fluency. This ambiguity suggests that the handwriting task used in this study might not fully capture the aspects associated with working memory and VMI.

Second, as noted, the high stabilities in handwriting fluency left little variance to be explained by working memory and VMI, respectively, which could explain the absence of longitudinal effects. When starting school, children have already gained some experience with the handwriting (e.g., controlling the pen to trace a line), and individual differences between children have already been established stronger than we expected. From today's perspective, thus, one might argue that this study started too late in children's handwriting development and should have started earlier when the handwriting might be less fluent, pen movements are more disruptive, and when individual differences are most likely less stable, for instance, in kindergarten (Faber et al., 2024). However, for educational practice, these high stabilities are very informative, underscoring the need for early detection of risk factors and difficulties to foster children's school readiness in its many facets.

Another limitation is that children copied words, which might have been a too easy task. The copy task is appropriate for children at the beginning of handwriting acquisition but becomes less demanding with increasing writing practice. Against the background of several studies pointing out the relevance of cognitive control when the task is novel or challenging at an adequate level of a child's development (Maurer & Roebers, 2021; Puranik et al., 2019), the longitudinal nature of our study with identical measurements might thus have impacted the results. Furthermore, as mentioned above, word copying may engage different levels of processing compared to tasks like writing dictated words, which require recalling spelling rules, phoneme-grapheme correspondence, and retrieving letter shapes. As suggested by van Galen's model (1991), additional levels of processing might make writing more complex and make it more cognitively demanding.

Despite these limitations, this study offers innovative and valuable insights into the development of handwriting fluency and associated mechanisms (i.e., working memory and VMI), independent of verbal aspects. It uniquely contributes to the understanding of the handwriting process by considering several kinematic measures of pen movement fluency during the first year of handwriting instruction. To better understand how cognitive factors are related to pen movement fluency in writing, future studies should explore the separate and overlapping associations between handwriting fluency, verbal aspects, and cognitive skills.

5. Conclusion

In conclusion, using a longitudinal design, this study shows that handwriting fluency becomes independent of working memory and VMI early in handwriting development. The fast development of handwriting fluency is encouraging, as the early release of cognitive capacity allows children to increasingly focus their attention on verbal aspects of writing, such as spelling, and text generation. Furthermore, the findings underline the importance of early handwriting skill levels when predicting later handwriting, suggesting that early exposure to handwriting may play a critical role in developing proficient handwriting skills.

CRediT authorship contribution statement

Lidia Truxius: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michelle N. Maurer:** Writing – review & editing, Software, Resources, Conceptualization. **Judith Sägesser Wyss:** Writing – review & editing, Software, Resources, Funding acquisition. **Claudia M. Roebers:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization.

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Declaration of competing interest

None

Appendix A

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. NIV T1	-																			
2. NIV T2	.41***	-																		
3. NIV T3	.30***	.57***	-																	
4. Pen stops T1	.61***	.25***	.23***	-																
5. Pen stops T2	.25***	.57***	.37***	.32***	-															
6. Pen stops T3	.29***	.33***	.58***	.40***	.41***	-														
7. Pen lifts T1	.52***	.23***	.20***	.81***	.31***	.39***	-													
8. Pen lifts T2	.23***	.48***	.34***	.38***	.73***	.47***	.46***	-												
9. Pen lifts T3	.29***	.31***	.46***	.40***	.40***	.63***	.51***	.58***	-											
10. Verbal working memory T1	-.06	-.04	.06	-.19***	-.13***	-.10	-.20***	-.22***	-.15**	-										
11. Verbal working memory T2	.03	.08	.14**	-.17**	-.09	-.11	-.21***	-.18***	-.08	.42***	-									
12. Verbal working memory T3	.03	.01	.05	-.14*	-.06	-.14*	-.21***	-.20***	-.18***	.44***	.49***	-								
13. Visual-spatial working memory T1	-.04	.02	-.02	-.11*	-.09	-.12*	-.15**	-.10	-.15**	.31***	.20***	.17***	-							
14. Visual-spatial working memory T2	.07	.07	.02	-.03	-.09	-.09	-.08	-.20***	-.15**	.26***	.34***	.29***	.43***	-						
15. Visual-spatial working memory T3	.01	-.04	.00	-.11*	-.05	-.05	-.16**	-.12*	-.11*	.28***	.31***	.32***	.32***	.42***	-					
16. VMI (fundamental shapes) T1	-.01	.03	.13*	-.15**	-.10	-.06	-.26***	-.21***	-.05	.18***	.31***	.28***	.18***	.25***	.19***	-				
17. VMI (fundamental shapes) T2	.01	.10	.11*	-.05	-.06	-.09	-.21***	-.17***	-.09	.19***	.30***	.29***	.10	.18***	.17**	.42***	-			
18. VMI (fundamental shapes) T3	.11*	-.01	-.01	.00	-.04	-.20***	-.10	-.11*	-.12*	.09	.19***	.31***	.00	.20***	.18**	.31***	.48***	-		
19. VMI (complex shapes) T1	.13*	.08	.04	-.02	.00	-.06	-.18***	-.18**	-.12*	.23***	.30***	.28***	.20***	.29***	.22***	.51***	.27***	.31***	-	
20. VMI (complex shapes) T2	.02	.04	.08	-.18***	-.05	-.09	-.32***	-.18**	-.10	.25***	.32***	.27***	.13*	.31***	.23***	.47***	.46***	.30***	.56***	-
21. VMI (complex shapes) T3	.03	.01	.08	-.12*	-.07	-.15**	-.23***	-.19***	-.15**	.21***	.30***	.31***	.13*	.28***	.20***	.33***	.43***	.52***	.51***	.52***

Note. NIV = numbers of inversions in velocity; VMI = visuomotor integration.

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