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The effect of fine motor skills, handwriting, and typing on reading development

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ABSTRACT

Discussions on the contribution of motor skills and processes to learning to read has a long history. Previous work is essentially divided into two separate strands, namely the contributions of fine motor skills (FMS) to reading and the influence of writing versus typing. In the current 2 × 2 × 3 mixed, single-blind, and randomly assigned experiment, we tested both strands together. A total of 87 children learned to decode pseudowords in either typing or writing conditions in which their FMS were either impaired or not. Decoding gains were measured at pretest, posttest, and follow-up, with FMS and working memory included as participant variable predictors. Findings indicated that FMS and working memory predicted decoding gains. Importantly, children performed best when typing if in the impaired FMS condition. Results have implications for motor representation theories of writing and for instruction of children with FMS impairments.

Introduction

There has been long-standing interest and controversy in how motor processes relate to reading development and performance (Kiefer & Velay, 2016), with discussions receiving particular relevance in debates on whether children should learn writing or typing in school. Furthermore, in the case of

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reading and motor difficulties, handwriting has been seen as an added strain on children, which should be dispensed with (e.g., in Finnish educational reforms).

In terms of empirical evidence, two comprehensive strands of research appear particularly relevant in understanding how motor processes relate to reading performance. In the first strand, research has tested whether children's fine motor skills (FMS) influence (Suggate et al., 2016) and predict reading development (Cameron et al., 2012; Grissmer et al., 2010; Pagani et al., 2010; Suggate et al., 2019). In the second strand, research and discussion have focused on whether handwriting, in comparison with the motorically more simple skill of typing, is beneficial for reading development (Kiefer & Velay, 2016). Both strands of research appear relevant to solving the question of whether motor processes are involved in reading development, yet the two approaches have existed in somewhat parallel worlds, using different methodology and theory and, to some extent, reaching different conclusions with varying degrees of recourse to causality. Therefore, in the current study, we conducted, for the first time, an experiment testing the role of typing/writing and FMS on reading development in preschool emerging readers.

Definitions

Before turning to findings related to both strands of research mentioned in the previous paragraph, we first define FMS and early reading development.

Fine motor skills

FMS can be broadly defined as "small muscle movements requiring close eye–hand coordination" (Luo et al., 2007, p. 596). At a practical and specific level, FMS have many different labels (e.g., manual dexterity, hand–eye coordination, manual control, visuomotor skill, graphomotor skill, visual–motor integration). The most common FMS tasks are pegboard tasks, weaving/threading, posting coins, line tracing or copying, and tapping (Beery & Buktenica, 1982; Brookman et al., 2013; Petermann et al., 2011). In the current article, we use the term FMS to refer to the broader range of skills but focus particularly on manual dexterity in this study for several reasons.

First, research appears to indicate that manual dexterity, measured with pegboard tasks (which require small-grained movements, visual integration, and in-hand manipulation), are the strongest predictor of cognitive and academic skills (Brookman et al., 2013; Martzog et al., 2019; Suggate et al., 2019). Second, visuomotor and graphomotor measures (e.g., symbol or design copying) usually involve using a writing tool (e.g., a pencil) during task performance, which likely confounds reading performance because those that are better at operating a pencil are likely better at writing/reading (Abbott et al., 2010). A speed-based FMS measure that has little variety in required motor movements (i.e., rapid tapping) seems not to represent the kinds of FMS that educators believe might be important in child development (Ratzon et al., 2007: Sulzenbruck et al., 2011; van der Fels et al., 2015).

Reading development

Reading development includes early literacy, decoding, and reading comprehension skills. Early literacy skills are precursors to reading that can be measured before reading skill itself develops (Whitehurst & Lonigan, 1998). Although early literacy skills include a number of skills (e.g., letter knowledge, knowledge of letter–sound correspondences, phonemic awareness, concepts about print, early handwriting) (Molfese et al., 2011; Whitehurst & Lonigan, 1998), we concentrated on decoding skills because these most resemble reading of all the preliteracy skills and, as outlined below, theoretically provide a stringent test of the role of FMS in reading. Decoding skills refer to children's performance at converting written symbols into phonemes in a fluent manner (Kendeou et al., 2009). Research studies and syntheses consistently find that early decoding skills in kindergarten are the strongest predictor of reading development in the early grades (National Early Literacy Panel, 2008; National Reading Panel, 2000).

Strand 1: Links between FMS and reading development

Earlier we mentioned that there are two main strands of research that are relevant in understanding whether and how motor processes link to reading development. The first strand examines FMS as predictors of reading and cognitive development, generally using correlational and longitudinal designs. After presenting theoretical mechanisms, we briefly summarize findings.

Theories on links between FMS and reading

In terms of understanding why FMS and cognitive development relate, two main theories posit links, namely functionalism and shared activation.

Functionalism. Functionalism assumes that FMS play a role in acquiring and performing specific academic skills when these directly involve fine motor activity (Penner-Wilger & Anderson, 2013; Suggate & Stoeger, 2017). According to functionalism, having greater FMS may lead to greater engagement in graphomotor activities such as drawing or writing, which then improve reading through having more opportunities to learn to decode letters and words. Furthermore, during writing and reading instruction and activities, children who can write more quickly automatically have more resources free to focus on other aspects such as comprehension. Thus, according to functionalism, FMS should predict completion of writing activities and the amount learned during writing-based reading instruction.

Shared activation. A second and increasingly common theory proposes that FMS and cognitive activities, including reading, share common underlying skills and neural processes (Suggate & Stoeger, 2017). For instance, a set of theories propose that cognitive processes represent internalized motor actions (Inhelder & Piaget, 1968; Lakoff & Johnson, 2010), with motor and cognitive skills being considered by some to be stages along the same continuum (Glenberg & Gallese, 2012; Thelen, 2000). At a neural level, it has been proposed that neural circuits can be redeployed to serve different functions to bolster cognitive processing (Anderson, 2007). Implicated networks for commonalities between cognitive and motor processing include the motor cortex, premotor cortex, inferior frontal cortex, cerebellum, and mirror neuron system (Diamond, 2000; Fuelscher et al., 2018; Nishiyori et al., 2016; Zwicker et al., 2011). Accordingly, shared activation theories propose that greater FMS relate to more sophisticated neural architecture, which in turn benefits cognitive processing (Suggate & Stoeger, 2017).

Empirical findings on links between FMS and reading development

Before considering links between FMS and reading specifically, we first consider associations with cognitive skills because these play a role in reading (Ferrer et al., 2010). Understanding such relations provides insight into functionalism versus shared activation theories and therefore can help to better understand relations between FMS and reading development and underlying mechanisms. In general, research finds statistical correlations between children's FMS and their cognitive and academic development. Specifically, FMS link with reasoning, working memory, executive function, and crystallized intelligence in preschool children (Becker et al., 2014; Cameron et al., 2012; Davis et al., 2011; Dellatolas et al., 2003; Martzog et al., 2019; Roebers et al., 2014; Smirni & Zappala, 1989; Voelcker-Rehage, 2005; Wassenberg et al., 2005). Furthermore, work has found links between FMS and general language (Dellatolas et al., 2003; Grissmer et al., 2010; Pagani et al., 2010) and lexical development (Suggate & Stoeger, 2014, 2017). Links exist in normal populations as well as special populations (Brookman et al., 2013).

Turning specifically to reading, data from large-scale longitudinal studies indicate that FMS link to reading achievement. Grissmer et al. (2010) analyzed links between FMS and reading across three data sets. Findings indicate that graphomotor skills (i.e., design copy) predicted reading after controlling for social skills, academic skills, and demographic factors. Using various graphomotor and writing-oriented FMS tasks involving the use of a writing tool, similar associations have been found in Chinese samples (Lam & McBride, 2018; Wang et al., 2015).

Pagani et al. (2010) found that a mixed measure of FMS (manual dexterity and graphomotor, parent report) in kindergarten predicted reading in Grade 2. Dinehart and Manfra (2013) analyzed data from the Miami–Dade School Readiness Project. Children included in their analyses were tested in kindergarten, and then grade point averages and standard achievement tests were administered 3 years later in Grade 3. Their results indicated that only graphomotor skills, not manual dexterity skills, uniquely predicted reading achievement scores in Grade 3 (Manfra et al., 2017). Research from studies including a number of covariates has generally replicated and extended links between graphomotor or visuomotor skills (Cameron et al., 2012) or manual dexterity (Becker et al., 2014; Suggate et al., 2018, 2019) and reading.

To our knowledge, only one experiment has tested whether FMS causally relate to reading development (Suggate et al., 2016). In this experiment, kindergarten children were taught to read letters and words in three conditions, namely a pointing condition (no graphomotor demands), a writing condition (graphomotor demands), and an impaired writing condition in which a heavy counterweight was attached to the end of a pencil (high graphomotor demands). Importantly, to control for novelty effects, all conditions contained an identical looking pencil with a large "mushroom" at the end filled with either polystyrene or steel. Children were then tested at pre- and posttest on the words they had learned to read. Results pointed toward a causal link between graphomotor demands and reading acquisition, with children learning more in the writing condition over the pointing condition and, lastly, over the impaired writing condition (Suggate et al., 2016).

Strand 2: Writing versus typing effects on reading development

Turning to the second strand of research, studies have examined whether learning in typing versus writing conditions results in different reading gains and which neural areas are activated during typing and writing. Before examining this work, two key theories are presented.

Theories on the effects of writing versus typing on reading

Motor–grapheme representation theory. One dominant theory is that writing relates to reading because it enables richer letter or word representations (Kiefer & Velay, 2016). Specifically, it is thought that through writing letter representations become integrated into a broader visuomotor network (Dinehart & Manfra, 2013), perhaps encompassing motor along with visual and phonetic nodes during writing. At a neurological level, letter and word processing has been found to recruit sensorimotor networks (James & Gauthier, 2006; Longcamp et al., 2005; Wamain et al., 2012). In short, by writing letters instead of just reading them, processing can occur at a level that recruits motor circuits to facilitate reading performance (James & Engelhardt, 2012). Thus, according to this account, writing enrichens and embodies reading, improving reading and spelling (Kiefer & Velay, 2016).

Attention-to-form theories. An alternative account also predicts that writing improves reading but instead proposes that during writing children need to pay particular attention to the forms of the letters. This extra attention in turn leads to better grapheme representations, facilitating reading (James & Engelhardt, 2012). As such, the motor action of writing does not facilitate reading per se (Araújo et al., 2022) but enhances visual letter representations.

Empirical findings on the effects of typing and writing on reading

A number of correlational studies show that better writers are also better readers (Abbott et al., 2010; Aram & Biron, 2004; Fitzgerald & Shanahan, 2000; Kim et al., 2014; Molfese et al., 2011) also in logographic languages such as Chinese (Lam & McBride, 2018). Copying and writing skills are frequently identified in studies as being related to reading and writing skills, such that there is considerable overlap in both processes (Berninger et al., 1992; Fitzgerald & Shanahan, 2000). In a meta-analysis of 50 experiments, it was found that writing practice had large effects on letter recognition (Araújo et al., 2022). Interestingly, Araújo and colleagues (2022) argued that their findings were most consistent with the idea that handwriting improves letter recognition because it results in better visual recognition of the letters (Li & James, 2016).

A number of experimental studies have compared writing and typing directly, usually examining letter recognition following training in letter production for typing versus writing conditions (Kiefer et al., 2015; Ouellette & Tims, 2014; Vinter & Chartrel, 2008; Wamain et al., 2012). These studies generally include preschool and kindergarten children, typically finding that writing provides advantages for letter and word recognition over typing.

Finally, previous research has generally focused on either one strand or the other, that is, FMS and reading/writing or typing versus writing. However, one study compared typing versus writing while including a second and novel writing condition in which children wrote with a stylus on a touchscreen (Mayer et al., 2019). Mayer et al. (2019) argued that this condition was more taxing from an FMS point of view because of the lack of friction on the touchscreen. Their findings generally indicated that writing with pencil and paper resulted in the greatest performance, followed by typing and then writing with the stylus on a touchscreen.

The current study

Previous research from the first strand indicates that FMS link to early reading development (Cameron et al., 2012; Pagani et al., 2010; Suggate et al., 2019); however, reasons for these links are unclear. First, most of these studies were correlational, thereby not allowing causal inference. In the only exception to this correlational research, one experiment found that some FMS activity during learning to read led to the greatest learning gains compared with an impaired FMS writing condition and a no-writing condition (Suggate et al., 2016). However, the optimal condition also contained writing. Thus, the conclusion that some, but not too much, FMS involvement improves reading acquisition is confounded with potential writing effects, necessitating the need for a fully factorial (writing vs. FMS) design. In a similar vein, the increased FMS demands in writing with a stylus on a touchscreen in Mayer et al.'s (2019) study resulted in worse performance than pencil and paper and, interestingly, typing.

Turning to the second strand involving studies showing that writing is more advantageous than typing for reading, a similar confound is present. Specifically, from an FMS perspective, the writing conditions involve significantly greater FMS demands than the typing conditions. Both writing and typing require spatial perception via proprioception (Vinter & Chartrel, 2008), for example, for the perception of which key lies next to the other on the keyboard during typing and for how long the spine of the letter “n” is to differentiate this from the letter “h”. However, the fine manual control needed to manipulate a pen or pencil is likely more sophisticated than that of a key press. Accordingly, in studies showing the superiority of writing over typing for letter recognition, it is not known to what extent the greater involvement of the FMS system in writing is driving the advantages.

To clarify this issue, a fully factorial experiment would appear to be a next logical step, where children learn to read in a condition manipulating FMS using a heavy versus light pencil (Suggate et al., 2016) and in a second condition where writing versus typing is manipulated. Accordingly, we randomly assigned kindergarten children to learn to read in one of four conditions in a 2 × 2 × 3 (Pencil Manipulation: heavy vs. light pencil × Writing Manipulation: typing vs. writing × Time: pre vs. post vs. follow-up) experimental design. In the writing manipulation children either wrote or typed letters, and in the pencil manipulation participants wrote or typed using either a light pencil (with a polystyrene-filled cone attached to the end) or a heavy pencil (with a steel weight-filled cone attached to the end) (see Suggate et al., 2016)—while learning to decode letters and pseudowords.

Based on previous research, we expected two main effects. First, if FMS drive reading development, then consistent with the previous experiment using a weighted pencil to manipulate FMS (Suggate et al., 2016) it would be expected that the light pencil results in the greatest reading gains. Second, if writing is more beneficial than typing for reading, then there should be a main effect for the writing conditions. Finally, we expected an interaction effect. From an FMS perspective arising out of functionalism, impaired FMS children might benefit from typing because this reduces the cognitive demands on their impaired FMS—in which case children in the impaired FMS typing condition should perform better than children in the impaired FMS writing condition. We included control variables of FMS, working memory, and receptive vocabulary. Vocabulary was included as a general cognitive control, and working memory was included because of its role in early reading and following instructions in the experimental conditions. FMS were included because we wanted to test functionalism, whereby children with greater FMS should be able to better negotiate the FMS demands in the learning conditions. Finally, we recorded how quickly children progressed through the learning materials to test whether there were differences in exposure to the reading materials attributable to the experimental conditions.

Method

Participants

Participants in the main experiment originally comprised 95 kindergarten children from five preschools in Bavaria, Germany, with a mean sample age of 5 years (*SD* = 5.68 months). Kindergartens were recruited via a newsletter distributed by a statewide institute providing further training and education for preschool teachers. Subsequently, interested preschool teachers contacted the study personnel and enrolled their facilities in the study. Only children in the last year of preschool providing written parental consent and verbal assent were included in the study, and the study was approved by the university ethics committee. Of the children, 47.4% were female, 14% were left-handed, and 28.4% were reported by their parents to speak another language than German at home. Of the parents, 27.3% reported having a nationality other than German and 34.4% had attained a university degree, rendering this sample with a nationwide average level of education (Federal Bureau of Statistics, 2019).

Given the robustness of multilevel models in dealing with missing data (Raudenbush & Bryk, 2002), we included children if they completed the experimental conditions and completed at least two of the pre/post/follow-up tests. Children were offered a small incentive for their participation in the study, and an institution was randomly selected for free further training as an incentive to participate. An a priori power calculation conducted in G*Power (Faul, 2020) was run. We used the large effect for groups found in the Suggate et al. (2017) study using a similar pencil manipulation to the one employed here. The estimation for four between-participant groups, three repeated measures correlating at .60, a large effect for pencil manipulation (f = .40; this was η^2 = .18 in Suggate et al., 2016), and a power of .80 gave a required sample size of N = 56, with this being N = 132 for a medium effect size. Accordingly, we aimed for 100 as an approximate midpoint between these two estimates.

Measures

The main dependent variable was decoding performance for letters and words learned in the experimental conditions. In addition, we included control variables (i.e., working memory, vocabulary, and FMS) to test whether these related to learning in the experimental conditions. Parents also completed a questionnaire comprising questions about demographic information (i.e., child's date of birth, nationality of child and parents, spoken languages at home, parents' education level). Further measures were included as part of a dissertation but were not analyzed here (i.e., letter-writing measure, graphomotor skill, tapping speed, screening for phonemic awareness). Handedness was determined by asking children to write their names on a sticker book and observing which hand they used to do this.

Decoding skill

Immediately before and after the block of experimental conditions, and at a follow-up testing 16.30 days later, children completed a decoding test. The decoding test contained the letters and pseudowords learned during the experimental conditions. Children were asked to name the sounds that corresponded to the letters or words included in the experimental conditions. Note that in German, in comparison with English, there is a greater overlap between the sounds and names of letters. For the first four of the presented words, children were allowed to decode the words as individual phonemes (e.g., "/i/ /n/ /e/ /b/"), whereas afterward only fluent reading of words was permitted (e.g., "neib"). If children were not able to sound out one or more of the letters in the target words, or if they read 10 consecutive letters or five consecutive words incorrectly, the test was discontinued and no further points were awarded. To capture variance at the lower end, thereby avoiding floor effects, we used a graded decoding task. The first four items were single letters to be sounded out individually. The next four were two-letter pseudowords that could be decoded letter by letter, after which points were awarded when the entire words were correctly read as a coherent words. A point was awarded for every correctly decoded letter at the beginning of the test and for every correctly read word later. The final score was the sum of all points.

Vocabulary

Children's expressive vocabulary was tested with the vocabulary test of the Kaufman Assessment Battery for Children–Second Edition (Kaufman & Kaufman, 2015). Children were asked to name pictured objects presented one at a time. The final score represented the number of correctly named objects. According to the test manual, the test shows a good to excellent test–retest reliability of .89 for 5-year-old children and .90 for 6-year old children (Kaufman & Kaufman, 2015).

Fine motor skills

To measure FMS, a pegboard task was used. Pegboard tasks are popular, often-used, and validated tests to measure dexterity (Martzog et al., 2019). The task contains a board with 24 holes with a distance of 1.5 cm from one another and 24 pegs (length = 4 cm, diameter = 5 mm). Children were instructed to take one peg at a time with their fingers out of a container, place it into the closest empty hole, and proceed until all pegs were inserted. Children performed the task first with their right hand and then with their left hand. The score constituted the total time taken to insert 48 pegs (i.e., 24 with the left hand and 24 with the right hand).

Working memory

To measure working memory, the backward digit task from the Würzburger Vorschultest (Würzburger Preschool Test; Endlich et al., 2017) was used. The test instructor played an audio file containing a sequence of numbers, increasing in difficulty from two to four digits. After each sequence, children were asked to repeat the digits in reverse order. For each sequence length, three trials were provided, giving a total of 12 possible items. The final score was the digit span that was the longest correctly recalled reverse sequence.

Experimental materials and conditions

Children were randomly assigned to one of the four experimental conditions in either the writing manipulation (writing vs. typing) or the pencil manipulation (heavy vs light pencil).

Experimental materials

Pencil manipulation. To manipulate FMS, two types of identical looking but different weight pencils were used that were adapted from previous research (Suggate et al., 2016). Accordingly, children wrote or typed the letters in all conditions using the writing end of a funny looking "mushroom" pencil. Both sets of pencils differed markedly in their weight, hence requiring different levels of FMS to successfully operate them. The lighter pencils had a conical polystyrene attachment at the end weighing 30 g, and the heavy pencils had a conical mushroom attachment made from steel weighing 185 g. Both types of cone were covered in the same colorful plastic foil, red with white polka dots, making them resemble some kind of exotic mushroom or toadstool. Importantly, the pencils had the same appearance in each condition (heavy vs. light) to control for novelty effects.

Learning materials. In each condition, children were introduced to letters and pseudowords containing four to seven different letters (e, i, n, b, l, u, t). The letters were selected to sound like real German words, which we verified by having five adults rate the proposed pseudoword sets. Moreover, letters were included to deliberately include some that were similar in appearance (u, n) and that contained both hard and soft sounds (t, b). Pseudowords started with two letters and were lengthened over the training blocks to be up to eight letters long. Overall, the total intervention length comprised 119 items in 15 pseudoword sets. This broad amount of items was created to ensure enough words for all children to fill a total of 28 min of decoding intervention, although it was expected that many children would be able to attempt only a small portion of the total items.

Procedure

Due to the novel nature of the research and corresponding challenges in calibrating the difficulty level of experimental materials to children while maintaining their attention and achieving successful experimental manipulations, we first piloted the study (reported briefly) before beginning the main experiment (reported subsequently).

Pilot study

Before conducting the main experiment, we piloted the experimental paradigm on 43 kindergarten children. Across the course of the pilot study, we noticed that children participated somewhat unwillingly in the experiment and showed lower than expected learning gains across all conditions. Based on experimenter feedback, we believed that this might be due to the sessions being too long and hence taxing for the children and the heavy pencil being too heavy. To remedy this, we reduced each of the experimental sessions from 10 to 7 min, split these across 2 days, and reduced the weight of the heavy pencil from 300 to 185 g. Furthermore, we included an extra step repeating the letters after the learning phase and, if performance was low, again at the beginning of the third learning unit on the second day.

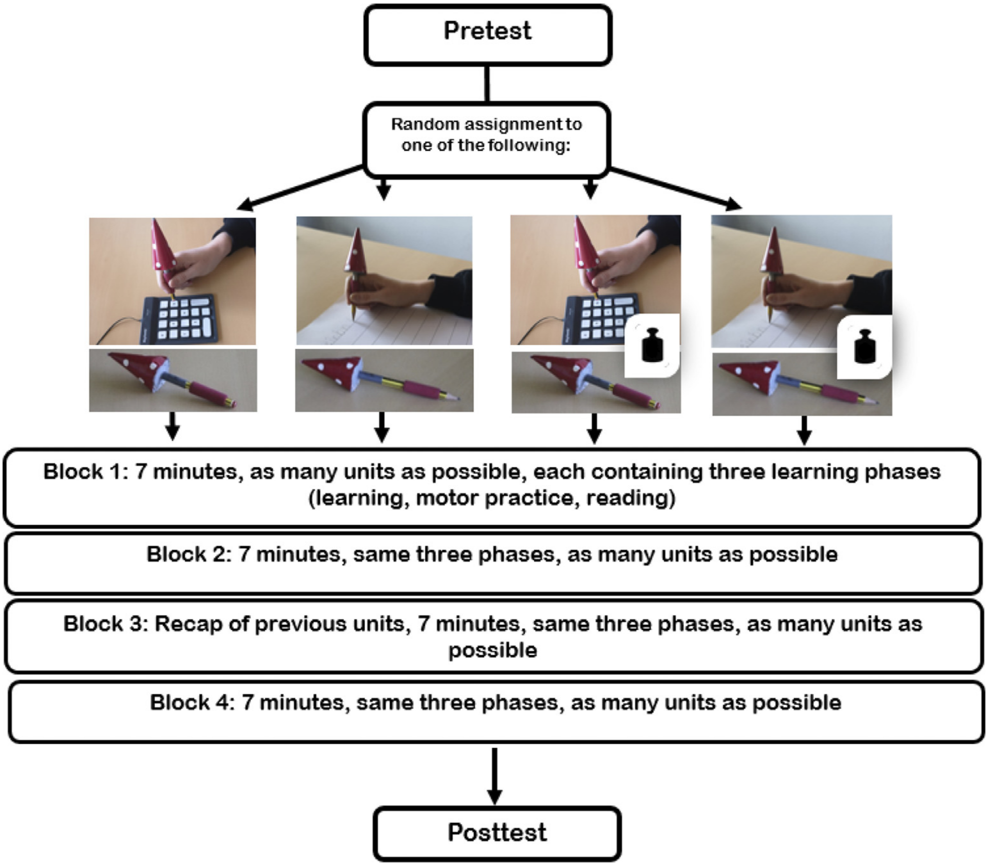

Fig. 1. Flowchart depicting experimental procedure.

Main experiment

Setup. An overall depiction of the experimental design and procedure is shown in Fig. 1. Children were tested individually in a separate silent room in the facilities of participating kindergartens. A laptop was placed on the edge of the table adjacent to the experimenter, and a screen was placed beside the children to show the letters and words to them and the experimenter separately. The keyboard used was an external number pad containing 20 keys (12 unmarked, 7 marked with letters, and 1 back key to allow for corrections).

Teaching blocks. Children were taught to decode the words in 7-min blocks. Words were presented one at a time, and each presentation had (a) a word teaching phase, (b) a motor practice phase, and (c) a reading phase. After these three phases, the next word was presented and so on until the 7 min for the entire learning block was completed. As depicted in Fig. 1, there were four blocks in total spread across 2 days. The phases contained the following:

> *Phase 1: Word teaching.* The experimenter read out the letter or word to the child, sounding these out in a clear articulation so that the child could learn to read the letters/words. Thus, when a word was presented, the experimenter first read the whole word, then repeated the sound of each letter, and again read the whole word to the child.
>
> *Phase 2: Motor practice.* After that, the child was asked to write the letter or word onto a lined paper (writing conditions) or type it with the help of a small keyboard into an empty box on the screen (typing conditions). During the typing or writing, the presented word remained visible on the screen.
>
> *Phase 3: Reading.* The child was instructed to provide the sound of the single letter while writing or typing each letter of the presented word using the writing (i.e., graphite) end of the pencil. After writing or typing the whole word correctly, the child was asked to read the word fluently aloud. If the child was not able to name a sound to a presented letter, the tester repeated it again. If a word was read incorrectly, the instructor repeated the whole word, every single letter of the word, and then the whole word fluently again. If an error was made again, a second repetition was introduced where the child again read the word and the instructor provided the correct word if an error was made. If an error was made on this second repeat, no more repetitions were provided and the next word was presented.

General structure. The test and intervention plan was divided into two separate test sessions on 2 consecutive days lasting approximately 50 min each and structured as follows. On the first day, children at the beginning of the pretest performed the decoding pretest and the first 7-min experimental learning block. Subsequently, a short 5-min break and the vocabulary test were implemented to ensure a short break between the two experimental learning blocks. After the break, the second 7-min experimental learning block was carried out, followed by a tapping task not reported here and the working memory task.

On the second test day, children were tested on four items from the previous day's experimental learning block at the beginning of the session to see how many letters and words had been retained. Depending on performance, the next learning block was begun. If children were able to read three of four or five out of seven learned letters (depending on the number of learned letters on the first test day), the next learning block was presented. If children were unable to decode three of four or five out of seven letters, the letters were repeated first a maximum of three times and then new words were presented. After the 7-min intervention block, the pegboard task and a 5-min break were scheduled, followed by the next 7-min experimental learning block. After another 2-min break, the posttest was performed (followed by two measures not reported here).

The follow-up decoding test was conducted 16.30 days (*SD* = 3.56) after the first intervention session. Although we targeted 2 weeks for the follow-up, it was not always possible to schedule an appointment in the kindergartens directly 2 weeks after each child's last test day, due to illness or clashes with kindergarten activities.

Experimental design and analyses

The design of the study was a mixed 2 × 2 × 3 experiment with random assignment to the experimental conditions. The two between-participant experimental conditions each had two levels, namely the pencil manipulation (i.e., heavy vs. light pencil) and the writing manipulation (i.e., writing vs. typing). Time had three levels and was a within-participant variable, with the decoding test being administered at pretest, posttest, or follow-up 16 days after the pretest.

Main analyses were conducted using mixed effect linear models (MELMs) to test the influence of the experimental conditions on decoding performance. MELMs represent a state-of-the-art method for modeling performance as a function of time and experimental condition, also allowing a test of the role of predictors (Raudenbush & Bryk, 2002). The Level 1 predictor was time (pretest vs. posttest vs. follow-up), and Level 2 predictors included experimental condition, learning items completed in the intervention, and in some models FMS and working memory. The experimental conditions were dummy-coded (pencil manipulation: 1 = heavy pencil, 0 = light pencil; writing manipulation, 1 = writing, 0 = typing). Analyses were conducted in R Version 4.1.0 using the merTools package (Knowles & Frederick, 2020) and lme4 package (Bates et al., 2015). Aside from the MELMs and homogeneity indicators, analyses were conducted in SPSS 26 (IBM Corp., Armonk, NY, USA).

Results

Seven children were excluded either because of incomplete data sets (*n* = 1) or because they could already read (*n* = 6). Concerning the latter, because we wanted to investigate the effect of FMS on early literacy development, we screened for children who already had sophisticated decoding skill. Six children had a pretest decoding performance of at least 2 standard deviations above the mean (i.e., $\geq$12), so these were excluded, leaving a sample size of *N* = 87 at pretest, 84 at posttest, and 81 at follow-up. This also greatly improved the skew and kurtosis (<2 at pretest).

Descriptive statistics and comparability of groups

Descriptive statistics for the decoding and control variables were calculated, and these appear in Tables 1 and 2. We also conducted a check on the random assignment to the groups by comparing scores using single factor analysis of variance (ANOVA). Groups were equivalent at pretest on the decoding measures, *F*(3, 83) = 0.72, *p* = .54, and on the additional predictor variables of FMS, *F*(3, 81) = 1.66, *p* = .18, working memory, *F*(3, 82) = 0.25, *p* = .86, age, *F*(3, 79) = 0.86, *p* = .47, and vocabulary, *F*(3, 82) = 1.52, *p* = .22.

Table 1
Descriptive statistics for control variables

		n	*M*	*SD*	Min	Max	*df*	*F*	*p*
Age (months)	Writing light pencil	23	71.22	5.88	60	84	3, 79	0.862	.465
	Writing heavy pencil	21	70.33	6.00	63	86			
	Typing light pencil	19	69.05	6.23	61	86			
	Typing heavy pencil	20	68.75	4.51	62	77			
Working memory	Writing light pencil	24	1.21	0.83	0,00	3,00	3, 82	0.249	.861
	Writing heavy pencil	21	1.14	0.65	0,00	2,00			
	Typing light pencil	20	1.05	0.83	0,00	3,00			
	Typing heavy pencil	21	1.24	0.70	0,00	2,00			
Pegboard	Writing light pencil	23	131.74	19.47	98	175	3, 81	1.658	.183
	Writing heavy pencil	21	140.90	17.47	113	176			
	Typing light pencil	20	139.60	17.16	111	171			
	Typing heavy pencil	21	144.48	23.78	110	203			
Vocabulary	Writing light pencil	23	11.74	4.94	0	19	3, 82	1.520	.215
	Writing heavy pencil	21	12.90	3.45	5	19			
	Typing light pencil	21	10.71	4.42	3	18			
	Typing heavy pencil	21	13.10	3.40	8	20			

Table 2
Descriptive statistics for decoding performance in the experimental conditions

		n	*M*	*SD*	Min	Max	*df*	*F*	*p*
Decoding pretest	Writing light pencil	24	2.29	2.99	0	10	3, 83	0.72	.543
	Writing heavy pencil	21	1.62	1.80	0	6			
	Typing light pencil	21	1.33	2.31	0	6			
	Typing heavy pencil	21	2.14	2.56	0	8			
Decoding posttest	Writing light pencil	22	9.14	11.61	0	10	3, 80	1.78	.157
	Writing heavy pencil	21	6.14	4.25	0	57			
	Typing light pencil	20	5.35	4.84	0	12			
	Typing heavy pencil	21	11.81	15.01	0	15			
Decoding follow-up	Writing light pencil	22	7.82	11.26	1	55	3, 77	1.18	.325
	Writing heavy pencil	20	5.15	4.43	0	14			
	Typing light pencil	19	5.32	4.11	0	13			
	Typing heavy pencil	20	10.45	15.84	0	62			
Items completed	Writing light pencil	24	22.88	12.98	0	59	3, 83	2.79	.046
	Writing heavy pencil	21	16.05	4.72	0	23			
	Typing light pencil	21	20.29	9.97	0	41			
	Typing heavy pencil	21	25.14	12.85	7	54			

Learning blocks completed across conditions

Next, we tested using single factor ANOVA as to whether groups received, and hence solved, different numbers of learning items in the experimental conditions. After the first 7-min learning block, the groups were not statistically significantly different, $F(3, 76) = 2.59$, $p = .06$; however, Bonferroni tests indicated that the heavy pencil typing group completed more items than the heavy pencil writing group ($p < .01$). After all four intervention blocks, the difference between groups was significant, $F(3, 83) = 2.79$, $p < .05$. Post hoc LSD (least significant difference) tests indicated that children writing with the lighter pencil proceeded further than those writing with the heavy pencil ($p = .04$) and that children writing with the heavy pencil completed fewer items than those typing with the heavy pencil ($p < .01$). This is depicted in Fig. 2.

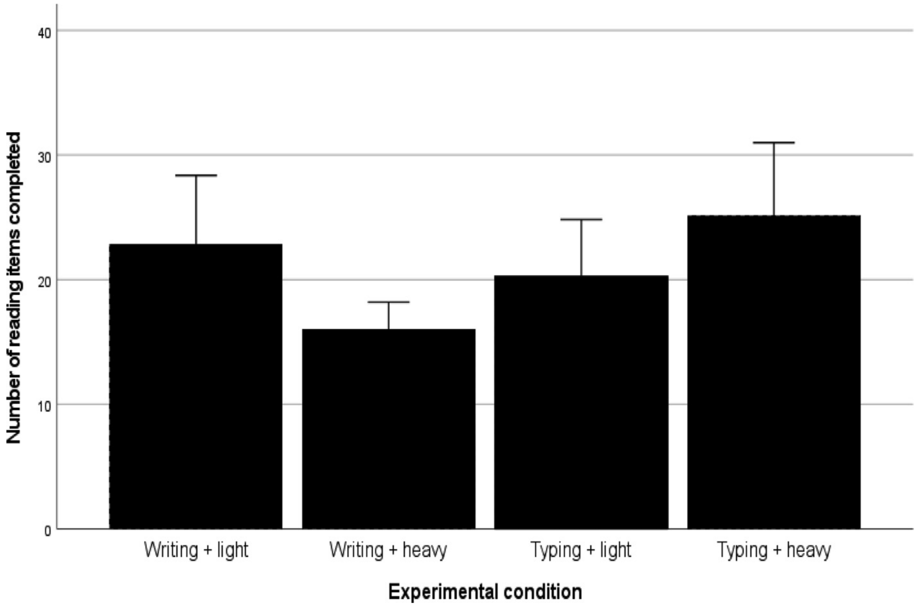

Fig. 2. Number of completed items in the training conditions as a function of experimental condition.

Effects of experimental conditions on decoding

Next, a MELM was run to test the effect that the pencil manipulation and writing manipulation had on decoding acquisition. We controlled for the number of completed intervention items to partial out any influence of learning exposure. The model appears in Table 3 and is displayed in Fig. 3 to facilitate interpretation. The findings from the first model in Table 3 indicate that children in all conditions scored significantly more points on the decoding test at posttest and follow-up than at pretest ($ps < .05$).

Performance in the writing manipulation condition

Findings in Table 3 indicate no main effect for the writing manipulation condition ($p = .96$) and no Writing × Time interaction at posttest ($p = .41$) or follow-up ($p = .55$).

Performance in the pencil manipulation condition

Data in Table 3 indicate no main effect for the pencil manipulation condition ($p = .49$) but indicate a significant Heavy Pencil × Time interaction at posttest ($p = .01$) and follow-up ($p = .02$). Accordingly, the heavy pencil condition resulted in greater gains at posttest and follow-up.

Table 3
Mixed effects model predicting decoding performance as a function of pencil type and writing condition with and without control variables

	Decoding performance			Decoding performance		
Predictors	Estimate	*CI*	*p*	Estimate	*CI*	*p*
(Intercept)	−9.81	−13.53, −6.09	<.001	−20.07	−33.58, −6.56	.004
Posttest	3.95	0.55, 7.36	.023	11.23	−2.66, 25.11	.113
Follow-up	4.02	0.56, 7.49	.023	17.21	3.17, 31.26	.017
Writing dummy	−0.46	−4.62, 3.70	.826	−0.17	−4.55, 4.20	.938
Heavy pencil dummy	−1.09	−5.41, 3.22	.618	−1.32	−5.74, 3.10	.556
Training items completed	0.55	0.44, 0.66	<.001	0.61	0.48, 0.73	<.001
Heavy Pencil Dummy × Writing Dummy	4.17	−1.93, 10.28	.180	4.52	−1.68, 10.72	.153
Posttest × Heavy Pencil Dummy	5.87	1.11, 10.63	.016	5.79	1.01, 10.56	.018
Follow-up × Heavy Pencil Dummy	5.31	0.48, 10.15	.031	5.69	0.78, 10.59	.023
Posttest × Writing Dummy	2.63	−2.07, 7.32	.271	2.20	−2.63, 7.03	.369
Follow-up × Writing Dummy	2.01	−2.72, 6.74	.404	1.63	−3.33, 6.60	.518
Posttest × Heavy Pencil Dummy × Writing Dummy	−7.93	−14.58, −1.27	.020	−7.49	−14.15, −0.84	.028
Follow-up × Heavy Pencil Dummy × Writing Dummy	−7.89	−14.63, −1.16	.022	−7.74	−14.54, −0.94	.026
Fine motor skills				0.08	−0.00, 0.16	.060
Working memory				−2.11	−4.30, 0.08	.059
Vocabulary				0.01	−0.29, 0.31	.951
Posttest × Fine Motor Skills				−0.07	−0.16, 0.02	.123
Follow-up × Fine Motor Skills				−0.11	−0.20, −0.02	.021
Posttest × Working Memory				2.46	0.15, 4.76	.037
Follow-up × Working Memory				1.54	−0.81, 3.89	.198
Random effects						
σ^2	30.40			29.18		
τ_{00}	$19.32_{\text{participant}}$			$18.74_{\text{participant}}$		
Intraclass correlation coefficient	.39			.39		
N	$88_{\text{participant}}$			$84_{\text{participant}}$		
Observations	254			244		
Marginal R^2 / Conditional R^2	.503 / .696			.536 / .717		

Note. Dummy coding: 1 = heavy pencil, 0 = light pencil; 1 = writing, 0 = typing. *CI*, confidence interval.

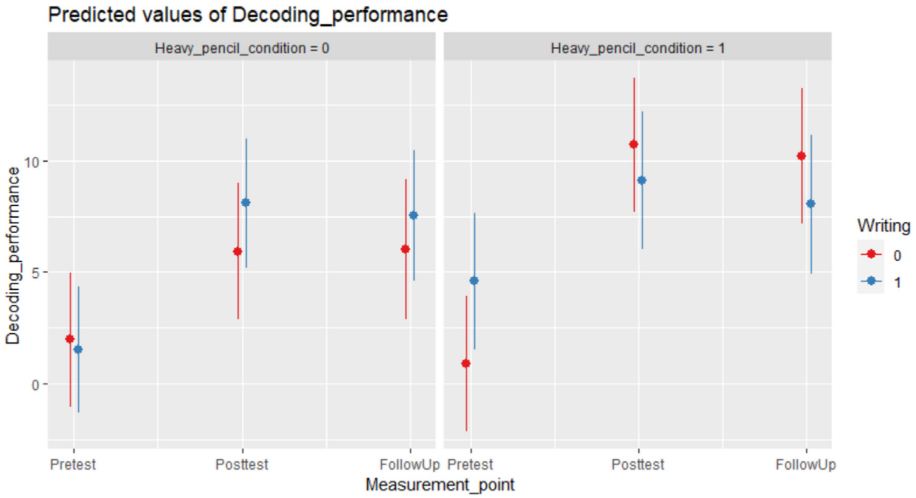

Fig. 3. Predicted values of decoding performance at pretest, posttest, and follow-up as a function of the pencil manipulation and writing conditions.

Interactions between manipulations and time

There were significant three-way interactions whereby children in the impaired FMS condition (heavy pencil) scored worse on the decoding tests at posttest (p = .03) and follow-up (p = .03) when in the writing condition. This indicates that the advantage for the heavy pencil was mostly confined to the typing condition at posttest and follow-up. The interaction is depicted in Fig. 3.

Predictors of reading performance

In a final model, we tested whether FMS, vocabulary, and working memory explained variance in decoding performance. FMS and working memory were entered into the model with interaction terms with time because we expected both variables to predict success at navigating the learning conditions that contain both strong working memory and FMS demands. Vocabulary was entered as a predictor without interactions because vocabulary was conceptualized as a cognitive control variable, not as a predictor of decoding skill acquisition. The model was added to Table 3. As can be seen in Table 3, the main findings from the simpler model (also in Table 3) remain. However, FMS and working memory showed significant interactions with time, indicating that those who performed better on the FMS pegboard task and those who scored more points on the working memory test also learned more at posttest and follow-up.

Discussion

In the current study, we conducted the first fully factorial experimental test of the contributions of FMS and writing versus typing to early reading acquisition. Using specially tailored pencils, we manipulated FMS, as has been done in previous research (Suggate et al., 2016). In addition, by including typing versus writing conditions, we endeavored to investigate the role that FMS demands play in learning to read. Specifically, in most previous research, typing versus writing comparisons have been confounded by the added FMS demands inherent in writing conditions, which may prove to be important because of links between FMS and reading (Cameron et al., 2012; Suggate et al., 2019). By increasing FMS demands in the typing condition (typing with heavy pencil), we could test whether increased FMS led to an advantage in writing versus typing (Araújo et al., 2022) or whether there is something unique about writing in learning to read. Finally, by including an impaired FMS condition and comparing typing versus writing, we could causally test whether children with fine motor impairments learn more from typing versus writing.

First, our data did not suggest that writing leads to greater decoding skill acquisition than typing. There was no evidence of a main effect for writing in any of the analyses, and children in the writing conditions neither learned to decode more words nor proceeded further through the intervention items than those in the typing condition. Accordingly, the current findings do not support the hypotheses that writing either improves attention to letters, or visual–motor representations thereof, in a way that measurably affects decoding skill acquisition. Accordingly, our findings are not consistent with the motor–grapheme representation (Kiefer & Velay, 2016) or the attention-to-form theories (Araújo et al., 2022).

The current findings did, however, show a significant effect for the pencil manipulation, with children in the heavy pencil condition learning more than children using the light pencil at posttest and follow-up. This finding appears to contradict the previous study using similar pencils (i.e., Suggate et al., 2016), in which the light pencil resulted in greater decoding gains. However, there was also a significant interaction, such that children writing with the heavy pencil achieved significantly lower learning gains than those typing with the heavy pencil, with this former group also completing fewer items after the first learning block and throughout the experiment. Thus, the advantage for the heavy pencil seems partly driven by the difficulty that children had in the heavy pencil writing condition. This finding was also supported by the observation that children in the heavy pencil condition made the slowest progress through the learning conditions, yet in the heavy pencil typing condition the greatest learning gains were found. Thus, consistent with Suggate et al. (2016), when FMS demands are too great, writing is a less effective means to impart decoding skills.

Interestingly, FMS were a significant predictor of children's decoding skill acquisition. This finding has two key implications. First, it supports previous research that FMS relate to reading acquisition (Cameron et al., 2012; Suggate et al., 2016), but now in a tightly controlled experimental paradigm. Second, the finding validates the FMS conditions, suggesting that these involved FMS demands as intended, such that those with better FMS learned more and progressed deeper into the learning blocks. Indeed, as shown in Table 3, there was a significant correlation between FMS and completed decoding items, indicating that those with better FMS completed more items. This finding held after controlling for both vocabulary and working memory. Turning to working memory, this was also a significant predictor of learning gains at posttest (see Tables 3 and 4), which is to be expected given the likely demands that the decoding instructions place on working memory.

The current findings generally suggest that FMS involvement during decoding acquisition results in strong learning effects that maintain to a follow-up test 2 weeks later despite children having been

Table 4
Pearson's correlation coefficients between the reading and predictor variables

		1	2	3	4	5	6	7	8
1.	Decoding pretest	–	.515**	.554**	.544**	−.002	−.02	.18	.18
	(*n*)		84	81	87	83	85	86	86
2.	Decoding posttest		–	.935**	.700**	.021	−.167	.26*	.18
	(*n*)			78	84	80	84	83	83
3.	Decoding follow-up			–	.734**	−.019	−.19	.18	.21
	(*n*)				81	77	79	80	80
4.	Completed items				–	.141	−.33**	,38**	.20
	(*n*)					83	85	86	86
5.	Age					–	−.22	.10	.07
	(*n*)						81	82	82
6.	Fine motor skills						–	−.16	.04
	(*n*)							82	82
7.	Working memory							–	.18
	(*n*)								85
8.	Vocabulary								–
	(*n*)								

* $p < .05$.
** $p < .01$.

involved in only four 7-min conditions. However, given the lack of added advantage for writing, the current findings are not initially consistent with embodied accounts suggesting that having a motor trace enhances a visuomotor letter representation (Kiefer & Velay, 2016). We were surprised by this finding; we expected, consistent with Suggate et al. (2016), that writing with the light pencil would result in the most powerful learning gains. Instead, the findings can be best taken to support functionalism because FMS enable greater engagement with complex reading–writing task demands, thereby improving decoding acquisition (Penner-Wilger & Anderson, 2013; Suggate & Stoeger, 2017).

Our finding, that impaired FMS children in the current study learned a superior amount from typing than from writing might be taken to support the idea that children with FMS difficulties should be taught to read via typing. Presumably, the mechanism in such a scenario would be that they had more resources free to concentrate on the decoding skill. However, we would caution against using the current findings to argue that writing should be dispensed with altogether, especially for children with FMS difficulties, because we do not know what the long-term consequences of this would be (Mangen, 2008). If it turns out that motor representations do indeed enrich graphemic representations, then research is needed to understand whether it is better to persist with writing at all costs, or dispense with this if underlying FMS prerequisites are impaired.

Limitations and future work

Turning to consider limitations, we included a condition in which children typed with a pencil to control for the novelty effect of the pencils with mushroom ends. Although this was necessary to provide a tightly controlled experimental design, this creates difficulties in generalizing findings to classic typing. Furthermore, it would have been informative to have included a no-FMS demands condition in which the experimenter points at the stimuli with the pencil (to control for novelty effects). This would have allowed us to replicate Suggate et al.'s (2016) study in which writing with some FMS involvement resulted in the greatest decoding skill gains compared with a control group without fine motor involvement.

In addition, it would have been interesting to include a longer experimental learning phase, extending beyond 28 min across four sessions to something longer representing school instruction. The reason for this is that it may simply take longer to establish writing traces in letter/word representations than could be tested here. One disadvantage in increasing learning time is that it would then become more difficult to control for extraneous learning factors such as self-teaching and parental/teacher instruction occurring outside of the intervention. Furthermore, we noticed that children in the heavy pencil condition became tired of holding the pencil over the course of the experiment, such that future work might need to vary the conditions to avoid fatigue or add measures of manual muscular endurance as predictors to the model.

Our assumption that the pegboard task is best conceptualized as a measure of manual dexterity is questionable because it contains a large speed component. For instance, Kail (1991) investigated processing speed across a variety of cognitive and perceptual–motor domains, finding marked improvements across childhood and remarkably similar trajectories regardless of the domain. This suggests that pegboard performance is confounded with cognitive performance, such that children with greater pegboard skills in the current experiment would also be expected to progress through more of the learning materials due to greater general cognitive abilities. This hypothesis would be most consistent with the shared activation theory because this posits that motor and cognitive processes overlap (e.g., Suggate & Stoeger, 2017). A broader issue arises regarding the measurement of FMS; instruments tend to confound speed, accuracy, and complexity of the motor task performed.

We also used a brief working memory test, whereas a longer task may have been a stronger predictor in Table 3. In addition, although not a key research question, we did not conduct a comprehensive handedness questionnaire but instead observed which hand children naturally used to write their own names and then encouraged them to continue using that same hand. Finally, future research should manipulate attention during the experimental conditions to determine whether the differing degrees of attention required in each condition, as opposed to FMS per se, resulted in the different learning gains. One idea would be to introduce an attention task that runs parallel to the conditions (e.g., pressing a key when a light appears and recording response latency).

Conclusions

In this experiment, we set out to test and combine two previously discrete strands of research, namely work on the influence of FMS on reading and the influence of typing versus writing on reading. Our findings generally showed that greater FMS involvement in typing resulted in the best learning gains, with the remaining conditions being approximately equal. Placing the aforementioned difficulties in this experimental work to one side, we tentatively conclude that motor processes and reading acquisition are linked and call for more work that teases apart the influence of motor representations from FMS demands in reading development (e.g., Mayer et al., 2019).

Data availability

Data will be made available on request.

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