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Improving literacy development with fine motor skills training: A digital game-based intervention in fourth grade

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ABSTRACT

Previous research has suggested that fine motor skills play a role in literacy development. However, it is necessary to confirm the causal nature of the relationships by using intervention studies. In addition, different explanatory mechanisms have been put forward to explain the relation between fine motor skills and literacy development. Executive functions and graphomotor skills are two possible mediators of this link, as they are related to literacy development and enhanced by motor interventions. Accordingly, we aimed to test the benefits of digital training of fine motor skills for children's fine motor skills as well as for their reading and writing skills, graphomotor skills, and executive functions. A controlled intervention was conducted with 205 fourth graders; for six weeks, half of the children played a digital game designed for motor training, and the other half played a control game training mathematics. Fine motor skills, literacy skills, graphomotor skills, and executive functions were assessed before and after the training. The results revealed that motor training improved not only some motor skills but also some literacy skills, graphomotor skills, and EFs. The findings confirm, for the first time, a causal relationship between fine motor skills practice and spelling by using an intervention design. Spelling improvement was nonetheless not mediated by executive functions or graphomotor skills improvement, suggesting that further studies are needed to better understand the underlying mechanisms.

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1. Introduction

Learning to read and write is a major challenge in education. Therefore, several studies have investigated which interventions could enhance this learning in both typical development and among children with learning difficulties. Most of these intervention studies have targeted low-level language skills, such as phonological awareness or decoding (Bus & van IJzendoorn, 1999; Suggate, 2016). However, non-language skills also play a role in literacy development. For example, fine motor skills (FMS) are linked to literacy development in kindergarten (Cameron et al., 2012; Doyen et al., 2017) and school-aged children (Lê et al., 2021; Schmidt et al., 2017). In addition, Lê et al. (2021) recently showed that the effect of FMS on literacy development is mediated by executive functions (EFs) and handwriting automation. Therefore, interventions targeting FMS may improve literacy by enhancing handwriting on the one hand and EF development on the other. However, intervention studies are lacking in terms of confirming these hypotheses; to date, studies conducted on the motor–literacy link have merely been correlational. A few studies have tested the benefits of motor training; however, none of them have tested the far transfer effect on literacy (Eddy et al., 2019). In this context, the present study aims to (i) evaluate how the practice of a video game specifically developed to train FMS could enhance literacy development in fourth grade and (ii) characterize the mechanisms involved in this training.

1.1. Fine motor skills and literacy development

Besides linguistic factors, FMS — the ability to coordinate small muscles in our hands and wrists — may also play a substantial role in literacy development. Several longitudinal studies have shown that FMS are predictors of later literacy skills beyond phonological and attentional skills (for a review, see MacDonald et al., 2016). Various literacy skills have been linked to FMS, including low-level skills such as word reading (Doyen et al., 2017; Grissmer et al., 2010; Lê et al., 2021) and word spelling (Berninger & Yates, Cartwright, et al., 1992; Doyen et al., 2017; Grissmer et al., 2010; Lê et al., 2021), as well as high-level skills such as text comprehension (Cameron et al., 2012; Lê et al., 2021) and text production (Berninger & Yates, Cartwright, et al., 1992). This motor–literacy relationship is not limited to the beginning of learning but is also found in older students, such as in third graders (Berninger & Yates, Cartwright, et al., 1992; Lê et al., 2021; Schmidt et al., 2017). For example, manual dexterity, assessed using a finger-tapping task, predicts spelling and text production from grades 1–3 (Berninger & Yates, Cartwright, et al., 1992). Similarly, unimanual dexterity, assessed using a peg-moving task, is linked to the reading speed, word spelling, and text comprehension of third graders (Lê et al., 2021).

Different explanatory mechanisms have been put forward to explain the relation between FMS and literacy development. First, it has been suggested that the effect of FMS on literacy is underlined by the development of graphomotor skills. Following the definition of Suggate et al. (2019), graphomotor skills are a subset of FMS that permit the manipulation of a pen and that are involved in handwriting. As the development of graphomotor skills is based on other FMS such as manual dexterity (Berninger & Yates, Cartwright, et al., 1992), better FMS may lead to improvements in graphomotor skills and handwriting. In turn, a more automated handwriting movement would permit the release of cognitive load during writing tasks and the reinvestment of resources in language processing (Suggate et al., 2018). This hypothesis is supported by studies showing that handwriting interventions improve spelling and text production (Santangelo & Graham, 2016). In addition, mediation analyses using regressions or structural equation modeling have confirmed that graphomotor skills, assessed using figure or letter copy tasks, explain the link between FMS and literacy in children from kindergarten to grade 5 (Dinehart & Manfra, 2013; Lê et al., 2021). A second hypothesis suggests that FMS affect literacy through the development of EFs that are high-order cognitive processes, such as inhibition and switching. The practice of motor activities may enhance EF development (e.g., Brock et al., 2018), thus indirectly improving literacy skills. In line with this hypothesis, a recent meta-analysis showed that the links between FMS and EFs, although small, remain robust and stable across development (Gandotra et al., 2022). In addition, in studies using structural equation modeling, mediation through EFs has been reported for kindergarteners (Oberer et al., 2018) and for children of 8–12 years (Schmidt et al., 2017). Importantly, the two mechanisms are complementary. A recent study conducted with third graders revealed that these two distinct pathways explain the effect of FMS on low levels of literacy (word reading and word spelling) as well as on high levels of literacy (text comprehension and text production; Lê et al., 2021).

In summary, the abovementioned studies suggest that FMS could play an important role in different dimensions of literacy development and highlight the importance of considering two explanatory mechanisms that both explain part of the effect of FMS on literacy. However, these studies used correlational methodologies, and they are insufficient to establish a causal link (Castles & Coltheart, 2004; Gandotra et al., 2022; Oberer et al., 2018). Conversely, intervention studies can allow experimental manipulation of FMS to confirm the abovementioned models. Testing this causal hypothesis is crucial since alternative explanations of the relationship between FMS and literacy have been put forward. For instance, it has been suggested that FMS do not exert a causal effect on literacy development but that both domains may be affected by the same supra-ordinated factor (Cameron et al., 2016). In this context, it is essential to use an intervention design to test the causal hypothesis and to validate the current models explaining the relationship between FMS and literacy.

1.2. Impact of motor training on motor and cognitive skills

The idea of testing the efficacy of motor training in school-age children is not new. Several studies have already investigated the effectiveness of interventions targeting FMS in typically developing children (for a review, see Eddy et al., 2019; Strooband et al., 2020). These studies revealed that motor interventions are effective in improving manual dexterity (Asakawa et al., 2019; Axford et al., 2018; McGlashan et al., 2017; Ohl et al., 2013). But most of these studies were conducted on young children aged 3–6 years (Strooband et al., 2020), and only a few of them also reported FMS improvement in older children aged 8–10 years (e.g., McGlashan et al., 2017).

Additionally, several of these studies suffer from limitations because they did not include an active control group or because they had a small sample size (e.g., [McGlashan et al., 2017](#); [Short et al., 2018](#)).

Importantly, these interventions can improve not only FMS but also graphomotor and cognitive skills. First, interventions targeting global FMS transfer to graphomotor skills, although they do not train pen manipulation ([Axford et al., 2018](#); [Ohl et al., 2013](#)). Similarly, FMS interventions that do not specifically train letter tracing improve the handwriting speed and legibility of kindergarten children ([Ghanamah et al., 2023](#); [Poon et al., 2010](#)); however, this transfer effect from motor training to handwriting has not been found in every case ([Hoy et al., 2011](#)). Second, motor interventions may also be transferable to cognitive skills. For example, [Hudson et al. \(2021\)](#) reported the beneficial effects of an intervention aimed at training FMS and gross motor skills on the motor skills, EFs, and numeracy of kindergarteners. Most of these interventions have implemented training targeting gross motor skills, sometimes combined with fine motor activities ([Contreras-Osorio et al., 2021](#); [Emami Kashfi et al., 2019](#); [Hudson et al., 2021](#); [Xue et al., 2019](#)). To our knowledge, only one study has investigated the transfer effect of an intervention specifically aimed at training FMS on cognitive skills. In the study, first graders improved their manual dexterity and arithmetic skills following a short FMS intervention of three weeks ([Asakawa et al., 2019](#)).

Although these results support the idea that FMS training could be efficient in improving literacy through graphomotor skills and EFs, currently, no studies have tested such transfer effects, and this issue still needs to be addressed.

1.3. A digital game-based intervention to train fine motor skills

Previous studies have used different types of training to improve FMS. Most of them are based on the practice of activities targeting manual dexterity and bimanual coordination, e.g., cutting and threading a lace (e.g., [Asakawa et al., 2019](#); [Ohl et al., 2013](#)), but others have used apps on tablets or computers ([Axford et al., 2018](#); [Butler et al., 2019](#); [Kazimoglu & Bacon, 2020](#); [McGlashan et al., 2017](#); [Poon et al., 2010](#)). In this context, it is interesting to question whether digital games can be effective tools to train FMS. On the one hand, studies in other fields have suggested that such tools may be more effective for learning than more conventional methods ([Wouters et al., 2013](#)). They may enhance learning through different ways: by fostering motivation ([Wouters et al., 2013](#)), by providing immediate feedback and rewards to the learner ([Erhel & Jamet, 2013](#); [Ronimus et al., 2014](#)), or by allowing for a more individualized progression of challenges, as these tools permit easy adjustment of the difficulty to the student's level ([Erhel & Jamet, 2013](#)). On the other hand, a negative effect of screen media on motor development has been reported by several studies ([Cadoret et al., 2016](#); [Martzog & Suggate, 2022](#)). The use of digital tools, such as tablets or smartphones, may indeed reduce FMS development because the movements required are not varied enough and are restricted to two dimensions ([Martzog & Suggate, 2022](#)). A study by [Lin et al. \(2017\)](#) supports this view. The authors reported that the manual dexterity and graphomotor skills of children who did not use touch screen tablets improved more than those of children who played FMS apps. However, this negative effect of digital applications has not been found in all studies. For example, a study conducted with kindergarteners indicated that the use of several digital apps soliciting FMS improved manual dexterity and graphomotor skills more than tabletop activities ([Axford et al., 2018](#)). In sum, the added value of digital tools to enhancing FMS remains debated.

Despite these divergent results, several studies have reported benefits of apps specifically designed to train FMS. Importantly, they report that these interventions could transfer to untrained FMS ([Butler et al., 2019](#); [Kazimoglu & Bacon, 2020](#); [McGlashan et al., 2017](#); [Poon et al., 2010](#)). For example, [Butler et al. \(2019\)](#) trained kindergarteners with a handwriting app on a tablet involving the manipulation of a stylus. Following the training, the manual dexterity of the children was improved relative to the control group. In another study, fourth graders played an app designed to train typewriting ([McGlashan et al., 2017](#)). The results revealed more improvements in the manual dexterity and visuo-motor control in the children who practiced the app compared to the passive control group. Although these results should be interpreted with caution because of limitations (e.g., small sample size), they support the idea that digital game-based training could be an effective tool for improving FMS.

In all the abovementioned studies, the activities required language skills (e.g., tracing letters on a tablet). However, to test the transfer effect of motor training on literacy, it is necessary to identify other digital games to better target the trained skill and exclude language components from motor training. In line with this idea, some authors have developed and implemented their own digital game to better control the skills trained by the game and the data collected during the training ([Kazimoglu & Bacon, 2020](#); [Poon et al., 2010](#)). For example, [Kazimoglu and Bacon \(2020\)](#) tested the effect on teenagers (16–19 years old) of the practice of platform video games presented on computers. They used a game specifically designed to train eye–hand coordination as well as visual attention; they also recorded the eye movements of the participants during gameplay. As in [Kazimoglu and Bacon \(2020\)](#), the game used in the present study was created in collaboration with the researchers to precisely adjust the tool to our research needs. More precisely, the game has been designed in such a way that its practice does not directly involve any of the three skills for which an indirect improvement is expected, i.e., graphomotor, executive, and language skills.

1.4. Present study

The aim of the present study was to investigate whether the practice of a game specifically designed to train FMS improves the literacy development of fourth graders. Previous studies have shown that FMS are linked to both low ([Doyen et al., 2017](#); [Lê et al., 2021](#)) and high levels ([Berninger & Yates, Cartwright, et al., 1992](#); [Lê et al., 2021](#)) of literacy skills. These correlational studies also suggest that the impact of FMS on literacy may be mediated by graphomotor skills and/or EFs ([Lê et al., 2021](#)). However, this hypothesis needs to be tested further. In addition, a few studies have reported that digital training could be an efficient tool for enhancing motor and cognitive skills. However, currently, no study has tested the transfer effect of such training on literacy. Therefore, the

current study aimed to test the effects of a digital game presented on tablets on both FMS and literacy. To this end, we conducted an intervention study in a school with a large sample of fourth graders. A specific video game was developed to meet the requirements of this research. This allowed us to provide sufficiently diverse FMS activities to train several motor skills as well as to limit the involvement of language skills, graphomotor skills, and executive control to specifically test the effect of FMS on literacy. The study included an active control group to overcome limitations found in previous studies; half the students were trained using a motor-skill-based video game, whereas the other half played mathematical video games to constitute the control group. Before and after the training, all students performed tests assessing FMS, literacy skills, graphomotor skills, and EFs. Based on previous work, we hypothesized that children who played the motor-skill-based video game would improve their FMS, graphomotor skills, and EFs—which have been shown to be mediators in the motor–literacy link—as well as different literacy skills (word reading, word spelling, and reading comprehension). In addition, the improvements in graphomotor skills and EFs should explain the improvements in literacy. Therefore, the present study has the following three objectives: (i) confirm the benefits of the game developed herein for FMS, (ii) test the transfer effect of FMS improvement on literacy, and (iii) test the mediation hypothesis by investigating the transfer effect of FMS training on graphomotor skills and EFs and the links between their improvement and literacy development.

2. Materials and Methods

2.1. Participants

A total of 205 fourth graders (mean age = 9;10 years; $SD = 4$ months; 113 girls) from 16 classes of 11 elementary schools in the Poitou-Charente region of France participated in the study. Before the beginning of the experiment, the schools were randomly assigned to either the control group or the experimental group. Prior to the analyses, data sets of three non-native French speakers were excluded. Thus, the analyses were performed on 202 children (control group: $N = 91$; mean age = 9;10 years; $SD = 5$ months; 50 girls; experimental group: $N = 111$; mean age = 9;11 years; $SD = 4$ months; 60 girls). No differences in terms of age or sex ratio were found between the two groups.

The study was in agreement with the ethical standards laid down in the Declaration of Helsinki, and it was validated by the Ethics Committee of Poitiers University. Informed parental consent was obtained from each participant prior to participation.

2.2. Tests administered in pretest and posttest

2.2.1. Fine motor skills

Three tasks were used to assess the students' FMS. The first two tasks were subtests of the M-ABC (Henderson & Sugden, 1992): unimanual dexterity (shifting pegs) and bimanual coordination (threading a nut on a bolt). The unimanual dexterity task involved shifting 12 pegs on a board as quickly as possible with the dominant hand and then with the non-dominant hand. Two trials were administered, and the better times of the dominant and non-dominant hands were added to obtain a single variable of unimanual dexterity. The bimanual coordination task involved threading a nut on a bolt as quickly as possible. Two trials were administered, and the better time was used as a dependent variable.

A third task was a subtest of the NEPSY – II battery (Korkman et al., 2012): finger tapping. The participants were asked to tap the thumb 20 times against the index finger as quickly as possible (repetition item) and then to tap the thumb 5 times against each finger in order as quickly as possible (sequence item). For both items, a time was recorded for both the dominant and the non-dominant hand, and the sum of the four times was used as the measure of finger tapping.

2.3. Literacy skills

Reading Skills. The participants' word/pseudoword reading skills were assessed using a test from the BALE battery (Jacquier-Roux et al., 2010). The participants were asked to read three lists of 20 items as accurately and as quickly as possible. The three lists comprised regular words, irregular words, and pseudowords. The total reading score corresponding to the number of correctly read items and the total reading time were used in the analyses.

Text comprehension was assessed using a text comprehension task developed by (Potocki et al., 2015), in which the children were asked to answer 12 questions after reading a short text by choosing the good answer among three possible answers. The number of correct responses was used in the analyses.

Writing Skills. Two spelling-to-dictation tasks from the BALE battery (Jacquier-Roux et al., 2010) and the L2MA (Chevrie-Muller et al., 1997) were administered. During the first task, the children had to write under dictation three lists comprising 10 regular words, 10 irregular words, and 10 pseudowords. The total score corresponding to the number of correctly spelled items was calculated. The second task comprised a text dictation. Two different scores assessing lexical spelling (/30) and grammatical spelling (/23) were calculated.

2.4. Graphomotor skills

Graphomotor skills were assessed using two tasks: the alphabet task and the figure copy task. During the alphabet task, participants must write letters in the correct order as quickly as possible in 15 s (Berninger & Fuller, 1992). In this study, children performed the task twice, and the higher number of correctly written letters was used as a dependent variable. The figure copy task was based on the

test proposed by Suggate et al. (2016): 20 non-alphabetic symbols based on Scandinavian runes were presented to the children, and the instruction was to copy as many symbols as possible in 30 s. The number of copied symbols was then counted and used in the analyses.

2.5. Executive functions

Inhibition. Inhibition was measured using a child-adapted Flanker task (Eriksen & Eriksen, 1974; McDermott et al., 2007) performed on a computer. In this task, the participant must indicate as quickly as possible the orientation of a fish located in the middle of a fish line while ignoring distractors. Fifteen congruent trials (with the target oriented in the same direction as distractors) and 15 incongruent trials (with the target oriented in the opposite direction as distractors) were randomly administered. The difference between the average reaction times in congruent and incongruent conditions was used as a dependent variable.

Shifting. Two tasks were administered to assess shifting. First, the children completed the Color Trail Test (D'Elia et al., 1996), which is a non-language version of the Trail Making Test (Reitan, 1971); the task was to connect numbers in the correct order as quickly as possible (control condition) and then to connect the numbers by alternating between two colors (shifting condition). For this test, the time difference between the control and shifting conditions was used as the shifting measure. Second, the children realized another shifting task, the creature-counting test from the TEA-Ch (Manly et al., 2006), in which participants had to count items in direct and reverse order. A shifting score was calculated based on the number of counting direction changes and the execution time.

2.6. Intervention training

The tablet video game “Brûme” was designed specifically for this study⁷ (<https://www.brume-le-jeu.fr/le-jeu/>). In this game, manual dexterity is required to progress through different worlds. The tool comprises three activities, each of which was specifically designed to train a specific FMS. The first activity, “Trace,” was constructed to train *visuo-motor control*: the player had to follow a target with their finger as precisely and quickly as possible. The complexity of the trail and the target speed increased during the player's progression. The second activity, “River,” focused on *pinch movements* by requiring the participant to catch targets without touching obstacles. The duration of the levels and the number of obstacles to avoid increased across the levels. The third activity, “Twister,” targeted *finger isolation and opposition of thumb to fingers*. In this activity, the player had to touch the target with different fingers of their hand. The number of solicited fingers in one level and the nature of the required movement (touch or move the target) determined the activity difficulty.

This game, which was the result of a collaboration between computer scientists and psychologists, has several advantages. It provides an attractive universe to the player with a storied progression to maintain the player's motivation throughout the training phase. In addition, it is equipped with an adaptive system that allows for adjusting the activity level depending on the player's difficulties. Hence, participants with motor difficulties can play easier levels, whereas participants with higher FMS can progress faster through these levels.

2.7. Control training

The control video games were selected following different criteria. First, they should provide educational content for use in the classroom. Second, they should not require language skills. Third, they should solicit FMS as little as possible. For example, games that solicit movements with several fingers (e.g., pinching an item or typing on a keyboard) or tracing movements (figures, letters, or numbers) were discarded. Two mathematics video games that follow the abovementioned three criteria were selected: “DragonBox Algebra” (<https://dragonbox.com>), which introduces equations, and game activities from the “calcul@TICE” software developed by the academy of Lille (<https://calculatice.ac-lille.fr>). The two games required the completion of arithmetic exercises in a playful environment.

2.8. Procedure

The study was conducted in the second part of the school year, from February to May. It followed a pre-post test design with an active control group and was conducted in schools under the supervision of trained researchers. FMS, literacy skills, and EFs were assessed before and after the intervention in the two groups to investigate the effects of the practice of the motor-skill-based game on these functions. The pretests and posttests comprised one collective session and one individual session. In the collective phase, the students performed the spelling tasks, the alphabet task, the figure copy task, and the reading comprehension task. Each participant then completed the manual dexterity task, the reading task, and the three EF tasks during an individual session with a trained researcher. After the pretests, both groups played an educational game on a tablet at school twice a week for six weeks. The intervention sessions were conducted in small groups of approximately six children and lasted 20 min. An experimenter supervised all the sessions for the experimental group and half the sessions for the control group. The teacher guided the other sessions in the control group. The pretests and posttests were separated by three months.

⁷ Note that the present study used a beta version of the game, and some activities may have evolved.

2.9. Statistical analyses

Before the analyses, outliers (data points below or above three *SDs* from the mean) were removed. Histograms and QQ plots were examined to assess normality (Gel et al., 2006). When the normality assumption was not confirmed, square transformation (for word reading accuracy, word spelling, lexical spelling, and text comprehension) and square root transformation (for word reading speed) were used to normalize the data.

First, we established correlations on the pretest measures of the whole group in order to ensure replication of previous studies showing links between FMS, literacy skills, graphomotor skills, and EFs (e.g., Grissmer et al., 2010; Suggate et al., 2018). Before analyzing the effect of the training, we compared the two groups using Student *t*-tests to check whether they were matched on pretest measures. Then, hierarchical linear mixed models were used to test the potential benefits of motor training on the different skills assessed herein (FMS, literacy, graphomotor skills, and EFs). The models included two fixed effects (group: experimental vs. control; time: pretest vs. posttest) and two hierarchical random effects (participants and classrooms). An interaction effect was expected on each measure to confirm that the students playing the motor-skill-based video game improved their performance more from the pretest to the posttest compared with the students in the active control group. Finally, to investigate whether the potential improvements in literacy were explained by improvements in FMS, graphomotor skills, and EFs, the targeted mediators were linked to differences between posttest and pretest in the experimental group, when significant interactions were found in the mixed models.

3. Results

3.1. Correlation analyses on pretest measures

Correlations were conducted on the pretest measures of the whole group. First, an analysis of correlations between the different literacy measures was performed. Second, correlations between FMS, literacy skills, graphomotor skills, and EFs were conducted in order to attempt replicating previous studies. For ease of presentation, correlations between FMS and literacy skills are first presented, and then correlations between the two potential mediating factors (i.e., graphomotor skills and EFs), and FMS and literacy skills.

3.2. Correlations between literacy skills

The correlations between the literacy measures are reported below in Table 1. As expected, the different literacy measures were strongly correlated (range: 0.35 to 0.84). The higher correlation was found between the two lexical spelling measures ($r = 0.84, p < .001$), supporting the validity of the measures.

3.3. Correlations between pretest measures of FMS and literacy skills

The FMS–literacy correlations are presented in Table 2, and the descriptive results of pretest measures are reported in Table 4 (columns 1 and 3). The analyses revealed small but significant relationships between FMS and literacy: all FMS measures were related to different spelling tasks (range: -0.16 to -0.24), and two of the FMS measures were related to reading (range: -0.20 to -0.24). For all these correlations, higher performances in FMS tasks (i.e., lower time of execution) were associated with higher scores in reading and/or spelling tasks.

3.4. Correlations between pretest measures of graphomotor skills, EFs, FMS, and literacy

The correlations between FMS, literacy, and the two possible mediators are reported in Table 3. The two measures that were considered possible mediators of the link between FMS and literacy were related to these two outcomes. Concerning graphomotor skills, figure copy was related to all the measures of FMS (range: -19 to -0.31), and the alphabet task was linked to all but one of the

Table 1
Correlations between Literacy Measures after Benjamini and Hochberg Correction.

	Word reading acc. (/60)	Word reading speed (s)	Word spelling – BALE (/30)	Lexical spelling – L2MA (/30)	Gram. spelling – L2MA (/23)	Text comp. (/12)
Word reading acc. (/60)	–					
Word reading speed (s)	– 0.58 * **	–				
Word spelling – BALE (/30)	0.75 * **	– 0.67 * **	–			
Lexical spelling – L2MA (/30)	0.78 * **	– 0.66 * **	0.84 * **	–		
Gram. spelling – L2MA (/23)	0.69 * **	– 0.57 * **	0.74 * **	0.75 * **	–	
Text comp. (/12)	0.46 * **	– 0.35 * **	0.44 * **	0.44 * **	0.48 * **	–

Note: * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 2
Correlations between Fine Motor Skills and Literacy after Benjamini and Hochberg Correction.

	FMS Unimanual dexterity – “shifting pegs” (s)	FMS Finger tapping (s)	FMS Bimanual coordination (s)
Word reading accuracy (/60)	– 0.20 **	– 0.20 **	– 0.13
Word reading speed (s)	0.08	0.12	0.07
Word spelling – BALE (/30)	– 0.24 **	– 0.22 **	– 0.16 *
Lexical spelling – L2MA (/30)	– 0.14	– 0.20 **	– 0.12
Grammatical spelling – L2MA (/23)	– 0.22 **	– 0.21 **	– 0.11
Text comprehension (/12)	– 0.24 **	– 0.09	0.01

Note: * $p < .05$, ** $p < .01$.

Table 3
Correlations between FMS, Graphomotor Skills, and EFs after Benjamini and Hochberg Correction.

	Graphomotor skills		Executive functions		
	Figure copy (number of copied figures)	Alphabet task (number of letters)	Inhibition – Flanker task (diff. of rt in each condition)	Switching – CTT (diff. of time in each condition in s)	Switching – Tea-Ch (time/change number)
FMS					
Unimanual dexterity – “shifting pegs” (s)	– 0.31 ***	– 0.37 ***	– 0.05	0.18 *	0.13
Finger tapping (s)	– 0.24 **	– 0.15	– 0.002	0.08	0.22 **
Bimanual coordination (s)	– 0.19 *	– 0.20 *	– 0.12	0.15	0.09
Literacy					
Word reading accuracy (/60)	0.28 ***	0.37 ***	0.08	– 0.23 **	– 0.19 *
Word reading speed (s)	– 0.23 **	– 0.39 ***	0.07	0.21 **	0.29 ***
Word spelling – BALE (/30)	0.40 ***	0.49 ***	– 0.03	– 0.19 **	– 0.26 **
Lexical spelling – L2MA (/30)	0.35 ***	0.42 ***	– 0.02	– 0.28 ***	– 0.23 **
Grammatical spelling – L2MA (/23)	0.39 ***	0.39 ***	0.01	– 0.28 ***	– 0.31 ***
Text comp. (/12)	0.25 **	0.27 **	– 0.06	– 0.22 *	– 0.16

Note: * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 4
Statistics for the Pretest and Posttest Measures of Each Group.

Task (scale)	Control group		Experimental group		Interaction	
	Pretest	Posttest	Pretest	Posttest	F	ηp^2
Fine motor skills						
Unimanual dexterity “shifting pegs” (s)	33.00 (6.14)	31.59 (5.03)	31.93 (4.31)	30.34 (3.67)	0.03	0.00
NEPSY finger tapping (s)	35.03 (7.67)	33.60 (7.78)	37.66 (7.48)*	33.26 (6.27)	7.75 **	0.04
Bimanual coordination (s)	16.19 (5.77)	16.02 (5.43)	15.53 (4.92)	16.07 (5.86)	0.88	0.00
Literacy						
Word reading accuracy (/60)	43.61 (9.84)	44.17 (10.61)	46.08 (7.18)	46.91 (7.37)	0.03	0.00
Word reading speed (s)	103.84 (48.70)	94.30 (45.30)	93.32 (37.90)	85.63 (34.19)	0.08	0.00
Word spelling – BALE (/30)	19.98 (6.67)	20.52 (6.54)	21.70 (4.75)	23.03 (4.57)	4.89 *	0.02
Lexical spelling – L2MA (/30)	12.25 (5.76)	12.87 (5.68)	13.45 (4.75)	14.44 (4.23)	0.65	0.00
Grammatical spelling – L2MA (/23)	5.52 (3.01)	5.91 (3.01)	6.40 (2.53)*	6.85 (2.86)	0.02	0.00
Reading comprehension (/12)	8.22 (2.89)	8.78 (2.75)	9.85 (1.99)* **	10.04 (1.80)	1.01	0.00
Graphomotor skills						
Figure copy (number of copied figures)	6.13 (2.50)	6.80 (2.82)	6.54 (2.08)	7.72 (2.58)	4.09 *	0.02
Alphabet task (number of letters)	12.48 (3.45)	13.73 (3.63)	13.68 (2.89)* *	14.68 (2.85)	0.75	0.00
Executive functions						
Inhibition – Flanker task (diff. of rt in each condition)	47.54 (52.24)	49.61 (60.08)	40.37 (56.39)	48.55 (63.18)	0.25	0.00
Switching – CTT (diff. of time in each condition in s)	61.54 (33.31)	54.74 (25.02)	51.97 (26.12)*	54.76 (24.05)	3.36	0.00
Switching – Tea-Ch (time/change number)	4.19 (0.98)	4.07 (1.01)	4.38 (1.17)	3.90 (1.00)	5.14 *	0.03

Note: Statistical differences between control and experimental pretests are indicated with an asterisk in column 4; $p < .05$, ** $p < .01$, *** $p < .001$;

FMS measures (range: -0.20 to -0.37). Significant correlations were also reported between all the graphomotor skills measures and all the literacy measures (range: 0.23 to 0.49). Concerning EFs, only switching was significantly correlated with FMS (range: 0.18 to 0.22). Similarly, while measures of literacy were significantly related to switching (range: -0.19 to -0.29), no correlation with inhibition was significant.

To conclude, the correlation analyses indicated small and medium-sized links between FMS, literacy, and the two mediating factors.

3.5. Benefits of the game-based motor intervention

The characteristics of pretest and posttests of each group are presented in Table 4. Pre-tests and post-tests results for the two groups according to gender can be found in Supplementary Materials (Table A1 and A2).

Before testing the benefits of the motor intervention, the two groups were compared on the different pretest measures (see Table 4, column 4). The control group obtained significantly lower performances than the experimental group on the grammatical spelling task, $t(169.9) = 2.18, p = .03, d = 0.34$; on the reading comprehension task, $t(153.7) = 4.44, p < .001, d = 0.72$; on the alphabet task, $t(169.5) = 2.62, p = .009, d = 0.40$; and on one of the switching tasks (CTT), $t(158.4) = 2.19, p = .03, d = 0.35$. The experimental group performed worse than the control group on one FMS task (finger tapping task of the NEPSY), $t(186.6) = 2.41, p = .02, d = 0.35$.

To test the benefits of the motor intervention, hierarchical linear mixed models were used with group (experimental and control) and time (pretest and posttest) as fixed effects and with participants and classrooms as random effects.

3.6. Fine motor skills

The analyses revealed a main effect of time on unimanual dexterity (i.e., shifting pegs), indicating that all the children improved their performance from the pretest to the posttest, $F(1, 194.37) = 13.45, p < .001, \eta^2 = .06$. However, the main effect of group and the interaction effect between group and time were not significant for this measure, group effect: $F(1, 10.49) = 0.93, p = .35$; interaction effect: $F(1, 194.56) = 0.03, p = .86$. Concerning finger tapping, no main effects of time or group were found, time effect: $F(1, 192.86) = 3.20, p = .08$; group effect: $F(1, 11.19) = 1.58, p = .23$. However, the interaction between time and group was significant: $F(1, 195.68) = 7.75, p = .006, \eta^2 = .04$. Post-hoc tests indicated that only the experimental group significantly improved its performance on finger tapping from the pretest to the posttest [control: $t(192.9) = 1.75, p = .28$, Cohen's $d = 0.25$; experimental: $t(199.9) = 6.08, p < .001$, Cohen's $d = 0.86$]. Although finger tapping did not show improvement in the post-test in the control group, it did bring the experimental group, starting from a lower baseline, to the same level as the control group. Finally, the analyses did not reveal significant main or interaction effects for bimanual coordination: time effect: $F(1, 185.55) = 0.32, p = .57$; group effect: $F(1, 15.49) = 1.63, p = .22$; interaction effect: $F(1, 191.24) = 0.88, p = .35$.

3.7. Literacy

A main effect of time was found for all the literacy measures: word spelling, $F(1, 196.22) = 4.89, p = .03, \eta^2 = .02$; lexical spelling, $F(1, 196.34) = 5.79, p = .02, \eta^2 = .03$; grammatical spelling, $F(1, 196.76) = 4.88, p = .03, \eta^2 = .02$; reading accuracy, $F(1, 192.16) = 4.43, p = .04, \eta^2 = .02$; reading speed, $F(1, 194.29) = 33.07, p < .001, \eta^2 = .15$; reading comprehension, $F(1, 189.47) = 4.61, p = .03, \eta^2 = .02$. This indicated that both groups improved their reading speed, comprehension, and spelling from the pretest to the posttest. In addition, a main effect of group was found on reading comprehension: $F(1, 9.46) = 6.68, p = .03, \eta^2 = .41$. The control group obtained lower scores than the experimental group. The group effect on the other measures was not significant: word spelling, $F(1, 9.73) = 1.69, p = .22$; lexical spelling, $F(1, 9.67) = 0.96, p = .34$; grammatical spelling, $F(1, 9.97) = 1.99, p = .19$; reading accuracy, $F(1, 8.65) = 2.15, p = .18$; reading speed, $F(1, 9.94) = 0.99, p = .34$. Finally, an interaction effect was found on word spelling: $F(1, 196.22) = 4.89, p = .03, \eta^2 = .02$. Post-hoc analyses revealed that only the experimental group improved its scores significantly after the training [control: $t(196.22) = 2.21, p = .12$, Cohen's $d = 0.32$; experimental: $t(196.18) = 5.92, p < .001$, Cohen's $d = 0.85$]. None of the other interactions reached significance: lexical spelling, $F(1, 196.34) = 0.65, p = .42$; grammatical spelling, $F(1, 196.72) = 0.02, p = .89$; reading accuracy, $F(1, 191.64) = 0.03, p = .86$; reading speed, $F(1, 194.26) = 0.08, p = .78$; reading comprehension, $F(1, 189.44) = 1.01, p = .32$.

3.8. Graphomotor skills

Concerning graphomotor skills, the analyses revealed a significant main effect of time for the two measures, indicating that the students from both groups improved their performances in the posttest session for the figure copy task, $F(1, 192.14) = 14.41, p < .001, \eta^2 = .07$ as well as for the handwriting task, $F(1, 195.96) = 26.26, p < .001, \eta^2 = .12$. No significant effects of group were found: figure copy task, $F(1, 9.54) = 0.86, p = .38$; handwriting task, $F(1, 11.99) = 3.72, p = .08$. However, the analyses revealed an interaction effect between group and time for the figure copy task: $F(1, 192.25) = 4.09, p = .04, \eta^2 = .02$. Post-hoc analyses revealed that both groups improved from the pretest to the posttest, but the size of the effect was larger in the experimental group compared with the control group [control: $t(192.14) = 3.80, p = .001$, Cohen's $d = 0.55$; experimental: $t(192.39) = 7.22, p < .001$, Cohen's $d = 1.04$]. The interaction between group and time did not reach significance for the handwriting task: $F(1, 195.67) = 0.75, p = .39$.

3.9. Executive functions

For the different EFs measures, the effect of time was not significant: inhibition task: $F(1, 176.55) = 0.07, p = .78$; CTT switching task: $F(1, 199.13) = 2.60, p = .11$; TEA-Ch switching task: $F(1, 179.42) = 2.58, p = .11$. However, the analyses revealed a significant effect of group for the CTT switching task, $F(1, 13.11) = 5.08, p = .04, \eta p^2 = .28$ with better performances in the experimental group than in the control group. The group effect did not reach significance in the two others measures: inhibition task: $F(1, 11.20) = 0.60, p = .46$; TEA-Ch switching task: $F(1, 12.38) = 0.46, p = .51$. Finally, the two-way interaction effect between group and time for the TEA-Ch switching task was significant, $F(1, 178.90) = 5.14, p = .02, \eta p^2 = .03$. The post-hoc tests indicated that only the experimental group improved its performance [control: $t(192.9) = 1.79, p = .28$, Cohen's $d = 0.26$; experimental: $t(199.0) = 6.02, p < .001$, Cohen's $d = 0.85$]. However, the interaction effect was neither significant for the inhibition task: $F(1, 172.85) = 0.25, p = .62$ nor for the second switching task (CTT): $F(1, 197.83) = 3.36, p = .07$.

To summarize the results, the training effect was calculated for all outcomes. For this purpose, the individual pretest and posttest performance of each measure was transformed into a z-score. Then, the difference between the posttest and the pretest was calculated for each participant. These results are presented in Fig. 1 and allow for a comparison of the average improvement in each group for all outcomes.

3.10. Correlation between improvements: testing potential mediators

We conducted further analyses specifically on the experimental group to investigate whether the effect of FMS training on spelling was mediated by EFs or graphomotor skills. First, correlation analyses between improvements (i.e., difference between the posttest and the pretest) in finger tapping, figure copy, switching, and word spelling were conducted. After Benjamini–Hochberg correction, results indicated that finger-tapping improvement did not significantly correlate with word spelling improvement, $r = .07; p = .52$, figure copy improvement $r = -.20; p = .14$, or switching improvement, $r = .07; p = .52$. Therefore, we did not further test mediation effects.

4. Discussion

Literacy development is supported by language and non-language skills. Previous studies have shown that reading and writing skills are linked to FMS across several age groups (Cameron et al., 2012; Lê et al., 2021; Schmidt et al., 2017). To explain this relationship, it has been suggested that FMS affect literacy development through graphomotor skills and EFs (Lê et al., 2021). However, the causal relationships between FMS and the other domains must be confirmed, especially with studies that do not just rely on correlational analyses. In this context, the main goal of the present study was to test these hypotheses by using an intervention design. With this objective in mind, we conducted an intervention study with fourth graders to examine whether practice in a digital game specifically developed to train FMS improved not only FMS but also literacy skills (word reading, word spelling, and reading

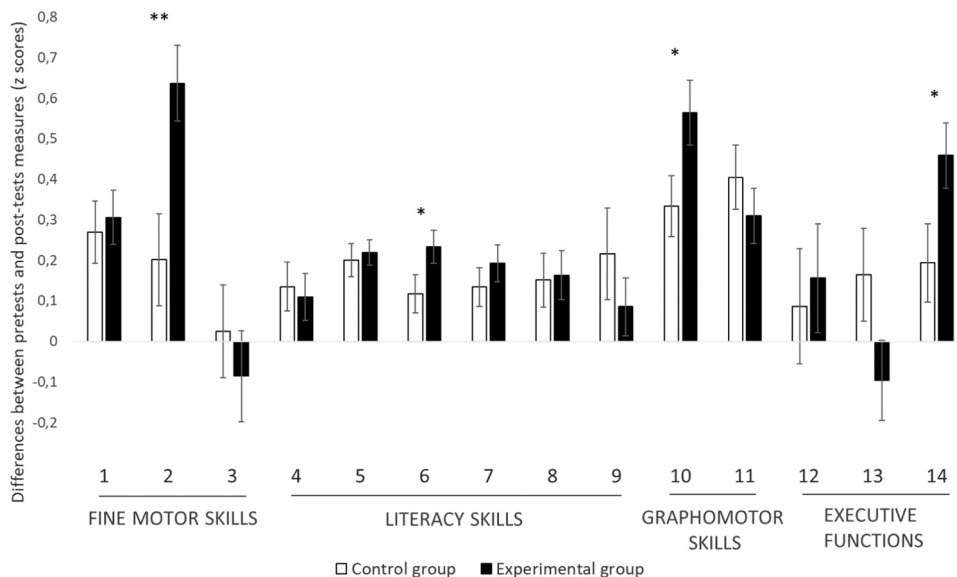


Fig. 1. Synthesis of improvements from the pretest to the posttest. Note: (1) Unimanual dexterity “shifting pegs”; (2) Finger tapping; (3) Bimanual coordination; (4) Word reading accuracy; (5) Word reading speed; (6) Word spelling – BALE; (7) Lexical spelling – L2MA; (8) Grammatical spelling – L2MA; (9) Reading comprehension; (10) Figure copy; (11) Alphabet task; (12) Inhibition – Flanker task; (13) Switching – CTT; (14) Switching – TEA-Ch. Improvements are indicated in black for the experimental group and in white for the control group. Significant interaction effects are indicated on the figure (* $p < .05$; ** $p < .01$). Error bars correspond to error standards.

comprehension), and two potential mediating factors: graphomotor skills and EFs.

4.1. Effect of digital game-based intervention on FMS

Before analyzing the motor-skill-based digital game's beneficial effects on literacy, we investigated whether its practice improved FMS. One of the strengths of the present study is the use of a digital game specifically developed for this study. Consequently, it was possible to precisely control the content of the motor training and adjust it depending on our research hypotheses. For example, we limited the involvement of language, graphomotor skills, and EFs in the activities, as the aim of the study was to evaluate the transfer effect from "pure" motor training to these other domains. Since this game was not validated beforehand, it was crucial to confirm that its use could improve FMS.

The results partly confirm this hypothesis, as the experimental group improved their performance more than the control group in one FMS measure: the finger-tapping task. Therefore, the present study suggests that FMS can be trained using a digital game for fourth graders. This is in accordance with previous findings that reported the beneficial effects of digital game-based interventions on FMS in kindergarteners (e.g., [Axford et al., 2018](#); [Butler et al., 2019](#)) and more rarely in older children ([Kazimoglu & Bacon, 2020](#); [McGlashan et al., 2017](#)). Importantly, our study included an active control group (one that played a digital game that did not focus on FMS) and was conducted with a larger sample size. Hence, the present study overcomes several methodological limitations (e.g., the absence of a control group or a small sample size) that have been pointed out in previous research and reinforces the idea that digital tools can be used for training some FMS. Despite these advances, results should be interpreted with caution as initial differences were observed on the finger-tapping task with lower performance in the experimental group in pretest.

4.2. Effect of FMS intervention on literacy skills

Second, and more closely linked to the main objective of this study, we investigated the transfer effect of the intervention on literacy to validate the current models explaining this FMS–literacy relationship. Before the training, correlation analyses were conducted to replicate previous findings showing links between FMS and literacy development in school-aged children ([Berninger & Yates, Cartwright, et al., 1992](#); [Lê et al., 2021](#); [Schmidt et al., 2017](#)). The analyses indicated that FMS are significantly correlated to both reading and writing skills. Although the correlations were small, they were similar to those reported in previous studies ([Macdonald et al., 2018](#)). They are a first step allowing us to go further in the testing of the hypothesis of an influence of FMS on literacy development.

The investigation of the benefits of the motor-skill-based game supports this causal hypothesis. Following the training phase, the experimental group improved more than the control group in one specific measure of literacy: word spelling. The present study is therefore the first to provide evidence in favor of a causal link between FMS and literacy development with an intervention design. However, the effect of training was limited to word spelling but did not extend to the other measures. First, it improved writing skills but not reading skills. This is consistent with our correlational analyses indicating that the links between FMS and literacy are stronger with spelling than with word reading and text comprehension. The stronger effect of FMS on spelling than on reading is logical, as writing tasks involve a motor component that could be enhanced by motor training. Conversely, it would be more difficult to transfer motor improvements to more distant skills, e.g., reading, which does not directly involve hand gestures. Second, training benefits were not found for all the writing measures. The FMS training improved word spelling, but its effect was not significant on the text-spelling-to-dictation task, which also assesses spelling. One difference between the two tasks is that the second task is more complex because it requires coordinating different levels of processing (phonological, orthographic, syntactic, semantic). It is therefore possible that the training was insufficient here to transfer to more demanding writing situations. Despite these limitations, the present study indicated for the first time that short fine motor training sessions over a six-week period improved not only FMS but also spelling even though the motor training developed herein did not have a language component.

4.3. Effect of FMS intervention on graphomotor skills and EFs

To better understand the influence of FMS practice on spelling, we then investigated whether the intervention also improved graphomotor skills and EFs. These two factors have indeed been put forward to explain the link between FMS and spelling (e.g., [Lê et al., 2021](#)). On the one hand, graphomotor automation would reduce motor constraints during writing tasks, allowing more resources for spelling processing ([Suggate et al., 2016](#)). On the other hand, FMS would affect the development of EFs ([Schmidt et al., 2017](#)) that are involved in academic achievement, including spelling acquisition ([Altemeier et al., 2008](#)). The present study replicated previous findings, as it indicated that these two factors were significantly correlated to both FMS measures and literacy measures in the pretest. However, concerning EFs, only switching, but not inhibition, was significantly linked to both literacy and motor skills. Previous studies have already reported that inhibition was less related to literacy or motor skills than others EFs ([Klupp et al., 2022](#); [Lê et al., 2021](#)) but these results are not found in all studies (for meta-analyses see ([Cortés Pascual, Moyano Muñoz, & Quilez Robres, 2019](#); [Gandotra et al., 2022](#)). Such divergences may result from differences in inhibition measures and further studies are needed to clarify the relations between these skills.

The investigation of motor training's beneficial effect on EFs and graphomotor skills revealed that the experimental group improved their EFs (assessed with a switching task) and their graphomotor skills (assessed using a figure copy task) more than the control group. Specifically, the present study supports the hypothesis that motor practice influences the development of EFs ([Brock et al., 2018](#); [Contreras-Osorio et al., 2021](#)). This hypothesis has already been tested using intervention studies. However, most of these

studies implemented sports interventions, whose benefits on cognition are not explained exclusively by the improvement in motor coordination (Contreras-Osorio et al., 2021), or implemented an intervention targeting both EFs and FMS (Brock et al., 2018). Similarly, concerning graphomotor skills, previous studies have shown that the training of general FMS could transfer to graphomotor skills even if the training activity does not involve the manipulation of a pen (e.g., Axford et al., 2018; Ohl et al., 2013). However, these few studies were restricted to kindergarten children. The present study extends these findings to fourth graders without learning disabilities.

The results of the intervention therefore supported current models suggesting that the impact of FMS on literacy is mediated by graphomotor skills and EFs because motor practice benefited both. To confirm this mediation hypothesis, we investigated the links between the improvements in FMS, graphomotor skills, EFs, and spelling. However, the analyses did not reveal significant correlations between them. This last result challenges the mediation hypothesis and suggests that FMS practice improved spelling through other pathways.

4.4. Limitations and future directions

Although the present study has reported an effect of motor training on all the assessed domains and therefore validates our hypotheses, it is important to point out limitations. First, the reported benefits remain small and are not found in all the evaluated measures. This contrasts with previous studies that have reported that FMS are linked to different EF measures and to diverse literacy skills, including word reading, in both kindergarten and grade 3 (Cameron et al., 2012; Doyen et al., 2017; Suggate et al., 2016). These divergences could be explained by the interventional nature of the study, as the effects of intervention studies are smaller than those of the correlational studies on which they are based (Foster, 2010).

Importantly, the small benefits of the training, including on FMS, suggest that the intervention could be enhanced for better results. For example, it is possible that the implementation of longer FMS training or evaluation of its long-term effect will lead to significant beneficial effects of motor training on other tasks, especially when they involve far transfer. In addition, the training only improved finger tapping, a fine motor skill which was highly similar to one of the training activities (i.e., Twister, that required children to touch the target with different fingers of their hand) compared to the other two assessed FMS. This may explain why it benefited more from the FMS training than the two other activities. The conception of the present study was based on a dissociation between two constructs in FMS: graphomotor skills that rely on the use of a pen and “more general FMS” that correspond to the other skills (Suggate et al., 2018). However, FMS are much more diverse, and non-graphomotor skills encompass different skills such as eye–hand coordination, finger agility, and object manipulation. In the current study, the training activities relied only on eye–hand coordination (follow a moving target with the finger) and finger agility (touch targets on screen with different fingers). However, due to the use of a tablet, object manipulation skills were not trained, and these skills did not seem to improve following the training. This result is in line with the concerns of Martzog et al. (2022), who suggested that screen media usage that implies only two-dimensional movements does not benefit tridimensional movements. In the future, it would be interesting to investigate more precisely which motor training features could modulate FMS improvement to provide more effective motor training. Specifically, the difficulty of transferring FMS digital training to more distant motor tasks needs to be addressed to identify the limitations of these interventions for FMS development.

A second important limitation concerns the mediation hypothesis. Indeed, the correlations did not reveal significant links between improvements in the four domains, raising important questions about how our training improved the different domains. One explanation is that unmeasured skills underlie the benefits. For example, the game activities implied visuo-motor control and visual perception whose improvement could have direct impacts on tasks like figure copy. In addition, we did not measure attention although it is related to both FMS and academic achievement (Grissmer et al., 2010). In general, the present study provides only partial explanations of the causal link between motor skills and written language, and further studies are needed to replicate and extend the results.

Despite these limitations, this study provides interesting avenues for exploring new pedagogical interventions for enhancing writing learning. First, although they are small, our results remain interesting because the intervention was relatively short (approximately four hours distributed over six weeks) and easy to implement (Kraft, 2020). The training involved practicing a video game that the students played without or with limited assistance. In more ecological situations, with less control of their practice, students should play more and for longer, perhaps leading to larger effects. In line with this applied perspective, it was important for us to assess the benefits of training in school-aged children although the benefits of digital game-based motor training have been poorly studied in this age group. Difficulties with written language processing often emerge in the middle of elementary school, and students with these difficulties are often those most concerned with specific interventions in the context of academic difficulties. Therefore, our intervention study provides support for the use of digital tools to enhance academic achievement in fourth-grade students.

Second, it is important to note that the present study was aimed at clarifying theoretical issues. Because of this, the training comprised “pure FMS” activities. However, it is reasonable to expect that combined interventions that, for example, involve motor training in language exercises would be more effective than pure FMS training. In line with this idea, previous studies have shown that handwriting interventions are more efficient when they involve letter tracing compared with only perceptuo-motor training (Hoy et al., 2011; Santangelo & Graham, 2016). In addition, recent studies have reported that the addition of gross and fine motor activities during letter and word learning improves letter knowledge more than traditional instruction in kindergarteners and first graders (Bara & Bonneton-Botté, 2017; Botha & Africa, 2020; Damsgaard et al., 2022). These studies support the added value of motor interventions combined with language intervention. However, it is necessary to confirm these advantages for the learning of literacy skills in children who are more advanced in their curricula.

Finally, another important issue that needs to be addressed is identifying which children benefit most from motor intervention. For

example, the difficulties of children with impaired motor control, such as in developmental coordination disorder (DCD), may be reduced by specific motor training. Importantly, DCD is frequently associated with written language impairments (Jover et al., 2013; Kaplan et al., 2001), and it is probable that the transfer of motor improvement to reading and writing may be more effective in this population.

To conclude, the present study is an important step in the validation of previous explanatory models of the motor–literacy relationship as it confirms, for the first time, that motor training could be transferable to spelling. Although there is a need for replication, the study brings new elements in favor of the influence of non-language skills on literacy development and opens an interesting avenue for providing easy-to-implement educational interventions.

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Declaration of Competing Interest

We have no known conflict of interest to disclose.

Data Availability

The data will be shared on osf after the publication.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.cogdev.2023.101363](https://doi.org/10.1016/j.cogdev.2023.101363).

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