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# Defining the relationship between fine motor visual-spatial integration and reading and spelling

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## Abstract

New research suggests that mechanisms involved in fine motor skills play an important role in reading and writing development. Extending past work that focused on fine motor skills measured in adolescence, the present study followed children longitudinally from ages 5 to 7 to examine early literacy and associated sets of fine motor skills, including visual-spatial integration and specfically grapho-motor skills. The current sample of 883 children ($M_{age} = 6.78$) from 80 geographically dispersed schools in Singapore was administered the Inventory of Early Development—3rd Edition (IED-III Standardised) assessment, to assess their visual-spatial integration and grapho-motor skills, and the Wide Range Abilities Test, 4th Edition (WRAT-4) to evaluate their reading as well as spelling in English. After controlling for age, maternal education, non-verbal intelligence, verbal memory, and inhibitory control, grapho-motor skill explained significant unique variance in reading (6%) and in spelling (3%) performance. This corroborates the role fine motor processes play in early literacy development in the context of Singapore, where there is less emphasis on non-academic skills even at an early age. Knowing the association of grapho-motor skills with these two literacy domains suggests potential avenues for improving future pedagogies for literacy skills.

**Keywords** Reading · Spelling · Fine-motor · Grapho-motor · Pre-school

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## Fine motor control

Fine motor skills involve the coordination of a group of small muscles and are needed to perform daily functions. Along with the acquisition of language skills, children also develop and refine a whole set of fine motor skills that profoundly alters and transforms their experiences with their environment and the people around them across their preschool and early childhood years. It is important to note that the term fine motor skill used in this study refers to the overarching term used to describe any activity done with the fingers or hands in tandem with the sensory organs such as the ears, mouth and eyes (for a review, see Bruininks & Bruininks, 2005), while specific sub-skills include visuo-motor, visual-spatial and grapho-motor, as described below.

Children should master by the age of two certain fine-motor skills that support grasping small objects, building with blocks, and scribbling (Bart et al., 2007). The synchronization of muscles underlying these activities is crucial for the development of later, more sophisticated manipulative movements such as writing, cutting, drawing, or dressing up and feeding oneself (Bruininks & Bruininks, 2005), and additional adaptive behaviors. More generally, children with greater motor dexterity are better adapted emotionally when transitioning from kindergarten to primary school (Bart et al., 2007; Pagani et al., 2010). Kindergarten teachers report that children with better pencil grip show quality handwriting skills and are able to manage their day-to-day activities such as feeding, tying shoelaces and dressing themselves in a more effective manner (McClelland & Cameron, 2019), which could contribute to a smoother transition to primary school. In addition, and as the focus of this study, children's fine motor development has been linked to their reading and writing development (Cadoret et al., 2018; Oberer et al., 2017).

Fine motor skills may be delineated into tasks involving *visuomotor control* (VMC—e.g., tracing, finger tapping, building with blocks or pegboard completion), and tasks that integrate motor with spatial abilities (*visual-spatial integration*, VSI—e.g., copying a geometric shape, picture drawings) (Carlson et al., 2013). Apart from copying abstract forms or pictures, another line of research examined how accurately and quickly children copy familiar and novel orthographic scripts (e.g., English, Greek, Vietnamese or Chinese). This form of copying alphanumeric items involves a subset of visual-spatial integration skills, and is referred to as *grapho-motor* skills (Lam & McBride, 2018; Wang et al., 2014; Suggate et al., 2017). While previous research studies focused on one of the components or on an aggregated score of components, this study focuses on visual-spatial integration as compared to grapho-motor and effects of each on reading and/or spelling. The three components of fine motor skills—visuomotor control, visual-spatial integration, and grapho-motor skill—and their relation to literacy are summarized in the next sections.

## Theoretical links for motor-literary skills in early years

Studies showing the unique contribution of fine motor skills to reading and math achievement have been replicated and extended to kindergarten (Pagani, et al., 2010; Grissmer, et al., 2010). These findings authenticate motor skills as a key element of school readiness. However, the results are mainly correlational, reporting significant concurrent relationships between motor and academic skills. Hence, it remains unclear whether motor skills lead to better academic skills, or if both are affected by a third, common variable. Moreover, there are still questions about how motor skills relate to key components of academic achievement during kindergarten.

The association of fine motor skills to reading and spelling is often viewed as an indirect one, a point that is central to this study. A third, common variable may affect both motor skills and academic skills. Broad cognitive ability, such as that measured as general intelligence or working memory or cognitive control, might underlie the apparent co-relation between skills in motor and academic domains. Cognitive variables play a key role in fine motor skills development, as mastering manual dexterity requires sustained attention, planning and deliberation (Adolph, Tamis-Lemonda, & Karasik, 2010; Conners, 2009; Diamond, 2000; McClelland & Cameron, 2019). Similarly, cognitive variables contribute to literacy development, as supported by reports of strong correlations between word reading performance and cognitive factors such as rapid automatized symbol naming, working memory, and broad intelligence (National Early Literacy Panel, 2008). Further, the same sets of cognitive skills associated with reading are also strongly correlated with fine motor abilities (Becker et al., 2014), such as attention (Conners, 2009), IQ (Ferrer et al., 2007), inhibitory control (Cartwright, 2012) and working memory (Preßler et al., 2014). This perspective suggests that fine motor abilities should not contribute any unique variance to literacy once general cognitive skills are taken into account.

Another point of view is taken from functionalism, which holds that fine motor skills may be the conduit for increased engagement in learning activities, which directly supports both domain general cognitive and domain specific academic development. The functionalism view is that children with greater fine motor skills are better able to engage in environmental activities involving manipulating or exploring objects, and this then opens up learning avenues previously closed to them. As such, increased opportunities to practice fine motor skills in early childhood classrooms should provide children with a literacy advantage (e.g., Cameron et al., 2016). Numerous studies show that visual-spatial integration has been linked with academic development through cognition to reading skills (at ages 5–7). The relation of visuo-motor coordination to literacy is less evident, while the contribution of visual-spatial integration to literacy may be specific to grapho-motor skills, which could have a more direct effect on literacy outcomes. That is, enhanced grapho-motor skills may contribute to accurate reproduction of correctly oriented lines and curves of letters and sequences in words, which becomes more automatic (Floyer-Lea & Matthews, 2004) and frees mental resources for higher-order information (i.e., decoding and encoding) rather than simple perceptual information (e.g., identifying letters) (Lam & McBride, 2018; McClelland & Cameron, 2019). Attention is re-allocated from simply naming and copying letters to making connections between letters and sounds and creating real words (McClelland & Cameron, 2019). Specifically, the use of motor movements for literacy learning may help children by introducing a procedural form of learning, which requires less conscious effort. Hence, it is expected that graphomotor skills have a close relation to spelling, which may be the source of the fine motor-literacy link, given the co-development of reading and spelling skills. This line of reasoning also suggests that cognitive skills pose more of a limiting factor on the fine motor to literacy link than a mediating effect. As a dominant method of teaching preschoolers to learn to read and to write, copying of print is the focus of several research studies investigating different language scripts and these studies showed that copying is strongly related to spelling development, including in English and in Chinese (Bourke et al., 2014; Lam & McBride, 2018; McBride-Chang et al., 2011; Wang et al., 2014). The current study addresses research questions related to the nature of the fine motor-literacy link: that is, whether there is a direct link of graph-motor copying to both reading and spelling in English.

## Fine motor components and early literacy

A systematic review of motor-language cascades from infancy to toddlerhood (Gonzalez et al., 2019) found that fine motor skills in particular foster language development from infancy to early childhood. Studies focusing on motor-to-literacy in the preschool years (5–6 years of age) report various outcomes depending on the motor subskills in question. A consistent finding is that tasks involving copying symbols (grapho-motor) is a better indicator of reading outcomes (Cameron et al., 2012; Carlson et al., 2013) compared with tasks involving tracing (visuo-motor) (Suggate et al., 2019). A number of studies find visual-spatial integration contributes to early literacy skills across different languages. Suggate et al. (2018) demonstrated that visuo-motor (Movement ABC task) and visual spatial integration (unfamiliar Greek letter copying task) are separable constructs with a factor analysis. They further reported with a sample of 6-year-olds that visuo-motor skill did not predict word reading, letter naming or writing when visual spatial integration, and IQ and attention, were accounted for. In another study, Chung et al. (2018) found significant correlations between copying geometric figures and reading and writing in non-alphabetic languages. Using a cross-sectional design, the authors examined 369 Chinese children from Hong Kong. The participants completed the DTVMI as a measurement for visual-spatial integration, an executive function assessment, and Chinese word reading and word dictation. After controlling for age, gender and maternal education, hierarchical regression analysis showed visual-spatial integration and executive functioning separately predicted Chinese word reading and writing. Thus, visual-spatial integration is demonstrably different from executive functioning and has unique effects on literacy unrelated to executive function effects.

Becker et al. (2014) reported in 4–6 year-old English speakers that visual-spatial integration (using the copying task in DTVMI-5) predicted concurrent English letter and word identification, accounting for 6% of the total variance after controlling for cognitive competency (measured as working memory and Stroop effects). Interestingly, they also found an effect of age, whereby visual-spatial integration was related to working memory only in the younger group of nursery schoolers (Becker et al., 2014). Carlson et al. (2013) also found across a wide age range (5–18 year-olds) strong concurrent relations of visual-spatial integration (symbol and shape copying task in DTVMI-5) to math and writing scores after controlling for visual-motor coordination (DTVMI-5 tracing).

Early grapho-motor skills have also been found to contribute to later language outcomes in longitudinal studies but may wash out over longer periods of time (Suggate et al., 2019). Considering that visual-spatial integration appears to be a significant contributor to literacy skills, it is of interest to examine whether this might be specific to the visual-spatial integration subskill of grapho-motor competence. Physically copying symbols and letter or word writing were observed to be more advantageous for building orthographic knowledge than visuo-motor coordination tasks such as tracing, keyboard typing, mentally recollecting or manipulating letter tiles. A majority of studies with school-age children have demonstrated a significant link for children's grapho-motor skills specifically, copying letters or graphemes, and learning to read or spell in the corresponding language: for Chinese (Chung, Lam, & Cheung, 2018; Lam & McBride, 2018; Wang et al., 2015), for Hindi (Bhide, 2018), for English (Cunningham & Stanovich, 1991) and for German (Suggate et al., 2018, 2019),

In a prior longitudinal study about Chinese language (Wang et al., 2015), grapho-motor skills for copying Chinese characters emerged as a unique predictor of Chinese word writing. Similarly, there was some support to show that copying and writing Hindi aksharas enables early language learners to build orthographic knowledge (Bhide, 2018). The results from non-alphabetic languages corroborate the findings from earlier work on alphabetic scripts, where Cunningham and Stanovich (1991) experimentally manipulated writing conditions and tested the effect on English spelling performance. Using a between group design, children aged 7 were instructed to spell words in three different ways. Groups had to either physically copy some words, type some of the words using a keyboard, or physically arrange letter tiles to make the word. Writing out the words was associated with higher accuracy scores compared to the other two conditions and this result remained true even at post-test. Together, these studies imply that physically copying letters or writing letters from memory can be viewed as a time efficient pedagogical tool.

An elegant study by Suggate et al. (2018) also experimentally examined the directionality of the grapho-motor-to-reading link, and this was extended to a younger age group. Preschoolers' pencil operation was manipulated while they learned to decode letters and nonsense words in a between group, randomized experimental design with pre- and post-testing. Children were assigned to one of three conditions in which they either copied a word using a light weight pencil, a metal weight pencil (impaired writing), or they simply pointed at the letters with the light pencil as they learned to read the words. Results from this experiment indicated that children learned the most decoding skills in the normal writing condition, followed by the pointing and impaired writing conditions, which did not differ from one another. The findings provide stronger experimental evidence that having poorer writing skills leads to poorer decoding skills and support the argument that there might be a causal relationship between grapho-motor and reading abilities. Importantly, this study suggests that the relation of grapho-motor to literacy skills can be seen at preschool. In a further study, Suggate et al. (2019) found that kindergarten grapho-motor skills contribute to later literacy outcomes at grade 1.

From the existing studies, a key take-away is that fine motor skills demonstrate concurrent relations with literacy across preschool to early childhood. Cross-sectional studies during the motor developmental stages spanning early childhood (ages 7–8) find fine motor and literacy relations. However, mixed results are reported in studies focusing on outcomes over time, with visual-spatial integration or grapho-motor skill at kindergarten predicting later language literacy outcomes in grade 1 (Suggate et al., 2019), but lesser effects of early fine motor skill on children's later academic achievement (Grissmer et al., 2010). Further, most studies focus on the association of reading to visual-spatial integration (e.g., copying) compared to either measured visuomotor skill (e.g., tracing) or grapho-motor skill (e.g. alphanumeric copying). The distinction between visuomotor control and visuospatial integration or more specifically grapho-motor skill has not been worked out, particularly at the early preschool stages. This study aims to fill these gaps in the literature by conducting a longitudinal examination of different kindergarten fine motor skills to primary school literacy outcomes. However, we concentrate on the visual-spatial skills since visuo-motor skills are shown to be only weakly related to literacy. Particular attention is drawn to the type of fine motor skills—either visual-spatial integration or grapho-motor—that contribute to this predictive relationship.

## Current study

Following Suggate et al. (2019), the current study examines whether a direct link of fine-motor to literacy skills is specific to grapho-motor or visual spatial integration, while controlling for cognitive skills, and whether such a link is stronger for spelling than reading. Focusing at the preschool to primary transition period, this study extends the question on relative contributions of specific grapho-motor versus general visuo-spatial integration skills to both early reading and spelling. Additionally, the present study extends the generalizability of findings to a different cultural and educational context, taking place in the Southeast Asian context of Singapore, where a classroom emphasis is noted to be based on more pre-academic skills than non-academic skills such as drawing, coloring, dramatic play or playing with blocks (Bautista et al., 2019). Findings from this study would therefore have important implications for educational practice and planning classroom activities to achieve optimal academic outcomes for children.

The following research questions frame and address the research aims of the study. Statistical analyses on the current data will address these questions and provide new knowledge that can inform future pedagogies for literacy skills.

1. To what extent do visual-spatial integration skills in Kindergarten 2 (K2) predict reading scores in Primary 1 (P1) after controlling for cognitive variables of non-verbal intelligence, working memory and inhibition?
   1a. It is expected that grapho-motor skill will be a stronger predictor than general visual-spatial integration based on previous findings that showed copying letterforms related to reading concurrently and over time.
2. To what extent do visual-spatial integration skills in K2 predict spelling scores in P1 after controlling for cognitive variables of non-verbal intelligence, working memory and inhibition?
   2a. It is expected that grapho-motor skill in particular will contribute to spelling, and that grapho-motor skill will explain a greater amount of variance in spelling than in reading. This follows from the functionalism line of reasoning, and that procedural learning through copying letters would be more directly linked to spelling performance.

## Context for the research

This study was conducted within the scope of a large-scale project on preschool education in Singapore (Ng et al., 2014; the 'Singapore Kindergarten Impact Project'—SKIP). Overall, the aim of SKIP was to examine a broader set of questions regarding how the preschool environment and pedagogical practices, together with home factors, influence children's learning and developmental outcomes and predict their readiness for primary school. Data was collected on a comprehensive battery of 1:1 child assessments to evaluate changes in children's academic and non-academic competencies. A total of 1538 Kindergarten 1 (K1) children from 80 preschools were recruited for SKIP. Eight hundred and eighty-three of these children with full data for the current research questions were included in the analysis. Other reports from the SKIP study include one paper by Khng and Ng, (in press) examining across a sample of 1248 children at K1 concurrent relationships between latent measures of fine motor control with mathematics and spelling outcomes and executive functioning. The combined construct of fine motor control (including reproducing shapes and figures and spontaneously writing letters) was found to distinguish between better and poorer spellers (who had better and poorer fine motor control, respectively). This differs from the present study that examines the longitudinal relationships between fine motor skills and literacy skills where the current focus is on teasing apart the subset of fine motor skills and differential relations to reading versus spelling. The SKIP sample also overlaps with other published articles (O'Brien et al., 2019; Yao et al., 2017) which did not analyze fine motor skills.

## Research design

The current study investigates the association of visual-spatial integration and grapho-motor skills to both the reading and spelling domains. The sample is derived from the previous longitudinal SKIP study (Ng et al., 2014) that held a broader set of research aims and did not specifically focus on the link between fine motor skills and literacy skills. The current study tracked children's performance from Kindergarten Year 2 to Primary grade 1 with the aim of identifying the relationship between visual-spatial integration and grapho-motor skill, assessed with Inventory of Early Development—3rd Edition (IED-III Standardised; French, 2013), and fundamental literacy skills in reading and spelling, assessed with standardized tasks in the Wide Range Abilities Test, 4th Edition (WRAT-4, Wilkinson & Robertson, 2006).

The research questions for the current study are specific to the sub-skills of visual-spatial integration and to reading and spelling scores and were addressed through hierarchical regression analyses. There are three main independent variables, two dependent variables, and six control variables overall. The three main independent variables are subtest scores from the IED-III, which include measures of (1) copying geometric shapes (B-3), (2) spontaneous drawing of a person (B-4) and (3) letter writing (B-7). The dependent variables are reading and spelling achievement scores from the WRAT-4. The control variables include non-verbal intelligence, inhibitory control (flanker test), working memory, K1 reading and spelling scores and demographic variables (e.g. age and maternal education).

## Method

### Participants

There were 883 child participants (435 males and 448 females) from 80 preschools in geographically dispersed locations across Singapore who were included in this study. The children in this study were native-speakers of English and Chinese ($n=638$), Malay ($n=107$) and Tamil ($n=138$) attending kindergarten in Singapore. All children were simultaneous bilinguals based on relative (English minus Ethnic Asian Language) age of language acquisition ($M=-0.26$ years, $SD=1.34$), relative proficiency (receptive vocabulary raw score $M=-7.91$, $SD=11.21$), and relative home input (proportion $M=0.24$, $SD=0.49$). Most children learned both English and their other language at nearly the same age and had similar proficiency between their two languages. while the proportion of home exposure was greater for English. The make-up of the sample is reflective of the demographics of Singapore, which is split into 4 main ethnic categorizations of Chinese (74.30%), Malay (13.40%), Indian (9.02%) and Other (3.28%) (Singapore Department of Statistics, 2019), with official languages—Mandarin, Malay, Tamil—corresponding to ethnic categorization.

### Measures

Amongst the overall battery of tasks, information on children's non-verbal intelligence, working memory, inhibitory control and visual-spatial integration skills was collected at Kindergarten 2 ($M_{age}$ = 63.15 months, *SD* = 3.89) and at P1 but only the K2 scores were included in the analysis. In a final wave of data collection at the beginning of Primary school 1 ($M_{age}$ = 80.85 months, *SD* = 3.79), the English language reading and spelling measures were administered that are the focus in this study.

### Predictive measures

*Visual-spatial integration skill* was measured with a relatively culture free measure, the Brigance Inventory of Early Development—3rd Edition (IED-III Standardised; French, 2013). Its scores have reliability evidence (e.g., internal consistency range = 0.80–0.97, test–retest = 0.92–0.99, inter-rater reliability range = 0.82–0.99). The task examines children's developmental and learning skills in five domains from birth to 7 years of age. Only the subtests measuring fine motor skills were included in the current study. The first two subtests—copying geometric shapes of increasing complexity (B-3), and spontaneous drawing of a person (B-4)—assessed copying and reproduction ability as visual-spatial integration. Test administration was tailored based on each child's chronological age. Each assessment has specific basal and ceiling rules, and administration was terminated when a ceiling and basal were established. Different types of visual-spatial abilities were the focus in this study.

*Grapho-motor skill* was measured using the Brigance Inventory of Early Development—3rd Edition (IED-III Standardised; French, 2013) sub-test B-7: Letter writing in sequence. Trained assistants scored these assessments after passing a reliability check (80% reliability). Higher scores would indicate better motor skills, specified as grapho-motor ability.

### Outcomes measures

*English reading* ability was assessed using the Wide Range Abilities Test, 4th Edition (WRAT-4, Wilkinson & Robertson, 2006). Children completed two subtests of letter naming (11 items) and word reading (55 items). Children were administered the blue form for reading at K1, K2 and P1. They were asked to identify letters and then read aloud as many words as possible. Administration of the word reading subtest was discontinued after 10 consecutive incorrect responses. A total reading score was obtained by summing the two subtests. Spearman-Brown split half reliability was 0.96.

*English spelling* ability was assessed using the WRAT-4 (Wilkinson & Robertson, 2006). The blue form was administered at K1, K2 and P1 and included letter writing (15 items) and word spelling (42 items). Letters and words were dictated, and each target word was presented in a sentence. The target word was read out, a sentence was then read with the target word in it, and then the target word was repeated (e.g. “and. The boys and girls. and.”). Word Spelling was terminated after 10 consecutive errors. The total number of correctly spelled words was scored and taken as the final score.

### Control measures

*Non-verbal intelligence* was assessed using The Raven's Coloured Progressive Matrices (Raven, 2003). It comprises of three sets of 12 items (Sets A, AB, and B) with items within a set becoming increasingly complex. Within each set, items are arranged in increasing order of difficulty. Children were presented with a pattern with a missing part in a matrix layout (either $2\times2$, $3\times3$, $4\times4$ or $6\times6$). Children were provided with a set of alternatives and had to choose the part that completed the pattern from the set. The test was discontinued when four consecutive incorrect responses were committed. The final score was a sum of the correct responses across all three sets.

*Working memory* was measured using the Backward Digit Recall (modified from Pickering & Gathercole, 2001). Children were provided with headphones for this task. There was a total of six experimental blocks (6 trials each), which progressed from a block with two numbers to a block with seven numbers. In each trial, children listened to a series of number (e.g. 5, 2) and had to verbally repeat the numbers in backward order (e.g. 2, 5). The research assistants recorded children's answers as correct or incorrect. The final score was the total number of correct trials.

*Inhibition skills* was tested using the flanker task. This task assessed children's inhibition skills. In this task (modified from Kopp et al., 1994), children were presented with a fixation point in the centre of the computer screen, followed by a row of five arrows facing either left or right with the target arrow. The target arrow appeared on its own (neutral condition) or was flanked on either side by two arrows facing the same (congruent condition) or the opposite direction (incongruent condition). In each trial, children were asked to identify, by key press, the direction the target arrow was facing. The first block consisted of 28 neutral trials, followed by two pure blocks of 28 congruent trials and 28 incongruent trials, or vice versa to counterbalance possible order effects. Each block of trials began with six practice trials with corrective feedback. The difference between scores in the congruent and incongruent trials was calculated and taken used as the final score in the current analyses.

Questionnaires were distributed to parents via their children's primary schools to collect *demographic information* about the child. This included information about their basic demographics (e.g., age, gender, ethnicity) and about the child's home background (e.g., parents' educational qualifications, housing type, household income, amount of time spent with various members of the household on a typical weekday/weekend).

## Procedure

### Selection and recruitment phase

Ethics approval was obtained from the authors' university Institutional Review Board (IRB). The sampling strategy targeted centers from a range of social strata, geographical locations, types of provider (both public and private), and whose fees were affordable to the majority of local families in Singapore. Private preschools charging high fees, therefore, were intentionally excluded. Participating kindergartens and centers in SKIP distributed parent letters and consent forms inviting them to have their children participate in the study. Those children whose parents provided written consent in the first wave of data collection were included as SKIP participants. Verbal assent was also obtained from children. Children were tested individually on site in the kindergartens in approximately 1-h sessions, with a larger battery of tasks completed over several days. The current study analyzes a subset of the tasks from the larger battery. All tests were conducted by trained research assistants with university degrees in education or psychology. The research assistants administered the tasks according to the instructions in the test manuals. To ensure accurate administration, each of the research assistants was trained before the data collection and was supervised by another senior research assistant.

Prior to the motor tasks, a handedness test was first conducted by asking children to show how they brush their teeth, ring a bell, cut a piece of paper with scissors, and draw a tree, in order to determine the dominant hand for the fine motor tasks and to build rapport.

### Data analysis approach

IBM Statistical Package for the Social Sciences (version 26, SPSS) statistical software was used to obtain descriptive statistics, to examine missing data prior to listwise deletion, and to perform hierarchical regression analyses. A summary of the variable means is presented in Table 1 for the participants who had complete data ($N = 885$). To examine whether there were significant effects of classroom level on the dependent measures, intra-class correlation coefficients (ICC) were estimated and used to calculate a design effect for each outcome (reading and spelling). This effect was below 2 for all outcomes (reading = 1.92, spelling = 1.45), indicating that between classroom effects would not need to be accounted for (Maas & Hox, 2005), and classroom level was therefore not included in the analyses. To examine effects on reading and spelling performance, hierarchical regression analyses were employed for the criterion measure. In all analyses, age and maternal education were controlled by entering them as a block of control variables in a first step of the multiple regression. The non-verbal intelligence, working memory, inhibition scores and K1 reading and spelling scores were entered as a block of predictor variables in the second step. Lastly, visual-spatial integration sub-tests and grapho-motor sub-test were entered as a block in the third step. Separate regression models were run for reading and for spelling.

**Table 1** Descriptive statistics of predictor and outcome variables

| Measure | N | Mean (SD) | Skewness (SE) | Kurtosis (SE) | Min | Max |
|---|---|---|---|---|---|---|
| Age (months) | 883 | 63.08 (3.88) | .04 (.06) | −.81 (0.13) | 55 | 74 |
| Maternal education | 883 | 7.25 (2.49) | −.98 (0.06) | .02 (0.13) | 0 | 11 |
| K2 non-verbal intelligence | 883 | 15.58 (5.04) | .33 (0.06) | .14 (0.13) | 2 | 35 |
| K2 working memory | 883 | 5.10 (4.38) | .47 (0.06) | −.37 (0.13) | 0 | 23 |
| K2 inhibitory control | 883 | 1.45 (3.58) | 1.55 (0.06) | 3.74 (0.13) | −10.38 | 17.96 |
| K1 reading | 883 | 17.94 (8.48) | 1.77 (0.07) | 4.68 (0.15) | 0 | 61.50 |
| K1 spelling | 750 | 13.76 (3.66) | −0.69 (0.07) | 1.15 (0.15) | 2 | 26 |
| K2 copying geometric shapes (B-3) | 883 | 4.77 (1.68) | −.05 (0.06) | −.08 (0.13) | 0 | 9 |
| K2 spontaneous Drawing (B-4) | 883 | 8.11 (1.82) | −.66 (0.06) | 1.26 (0.13) | 0 | 13 |
| K2 letter writing (B-7) | 883 | 20.73 (6.66) | −1.31 (0.06) | .44 (0.13) | 0 | 26 |
| P1 reading | 883 | 39.23 (14.45) | .09 (0.07) | −.59 (0.14) | 0 | 88 |
| P1 spelling | 750 | 20.78 (4.17) | .18 (0.07) | .63 (0.14) | 4 | 35 |

To address the two research questions, two sets of analyses were conducted. Raw data were entered into the analyses. First, correlations between literacy and fine motor skills were performed to check for zero-order relations and multi-collinearity. Secondly, hierarchical regression analyses were run to examine the amount of unique variance contributed to literacy by the visual-spatial integration and graphomotor predictors after controlling for demographic and cognitive variables.

*Inter-correlations between all measures* The inter-correlations between the predictor variables (age, non-verbal intelligence, working memory, inhibitory control, K1 reading and spelling and fine motor skills) and outcome variables (reading and spelling) were first examined using Pearson correlation (see Table 2). Amongst the fine motor measures, though interrelations were significant, the correlation coefficients were low ($r$'s = 0.11–0.25). Likewise, the literacy measures were significantly but weakly related ($r = 0.24$), implying that while the measures share common fundamental factors, each also measures unique skills. There were also moderate correlations between the predictor and outcome variables, particularly for reading, which was significantly related to both the control variables and the fine motor variables. Spelling was related to visual-spatial integration copying and letter writing, as well as working memory. Finally, the cognitive control

**Table 2** Correlations matrix among K1 and K2 predictors and P1 outcome variables

| Measure | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Age (months) | 1 | | | | | | | | | | | |
| 2. Maternal Education | −0.02 | 1 | | | | | | | | | | |
| 3. K2 non-verbal intelligence | 0.25** | 0.14** | 1 | | | | | | | | | |
| 4. K2 working memory | 0.141** | 0.17** | 0.31** | 1 | | | | | | | | |
| 5. K2 inhibitory control | −0.07 | −0.10** | −0.12** | −0.14** | 1 | | | | | | | |
| 6. K1 reading | 0.07* | 0.04 | 0.09 | 0.04 | −0.03 | 1 | | | | | | |
| 7. K1 spelling | 0.09** | 0.04 | 0.08** | 0.07* | −0.01 | 0.74** | 1 | | | | | |
| 8. K2 copying geometric shapes (B-3) | 0.15** | 0.01 | 0.16** | 0.12** | −0.10** | −0.02 | −0.01 | 1 | | | | |
| 9. K2 spontaneous drawing (B-4) | 0.11** | 0.10** | 0.18** | 0.16** | −0.04 | 0.17** | 0.25** | 0.11** | 1 | | | |
| 10. K2 Letter writing (B-7) | 0.14** | 0.18** | 0.23** | 0.23** | −0.15 | 0.09** | 0.08** | 0.20** | 0.20** | 1 | | |
| 11. P1 reading | 0.12** | 0.34** | 0.34** | 0.32** | −0.14** | 0.08* | 0.05 | 0.11** | 0.17** | 0.42* | 1 | |
| 12. P1 spelling | 0.01 | 0.15** | 0.08** | 0.13** | 0.001 | −0.01 | 0.01 | 0.10** | 0.06* | 0.19** | 0.24** | 1 |

*$p < 0.05$; **$p < 0.001$ (2-tailed)

measures and the fine motor measures were also related but weakly, suggesting that they measure discrete aspects. This justifies the approach of including each of the variables in the hierarchical regression models and examining the individual contribution of each visual-spatial integration skill to reading and spelling.

*Hierarchical regression analyses* Separate hierarchical regressions were run for reading and spelling outcomes. The same predictors were entered into each model in the same order for each of the two regressions. Step 1 consisted of control variables of age and maternal education. Step 2 included non-verbal intelligence, working memory, inhibitory control and prior literacy scores for reading and spelling obtained at K1. In Step 3, the sub-tests of the IED were included, in order to determine the amount of variance in reading and spelling outcomes that was explained by children's visual-spatial integration skills after accounting for cognitive abilities. Effect size (Cohen's $f^2$) was tabulated for each full regression model. According to Cohen's (1992) guidelines, Cohen's $f^2$ provides the effect size for hierarchical regression analyses of the variance in literacy outcomes accounted for by each predictor variable. A small effect size of 0.02 is likely, followed by a moderate effect size of 0.03–0.15 or a large effect size of 0.35 and/or higher.

## Results

### Descriptive statistics

The descriptive statistics of the variables are presented in Table 1. Judging from the means, there are no obvious floor or ceiling effects of the scores across measures.

### Examining normality and parametric assumptions

Before starting the analyses, the dataset was inspected for normality and homoscedasticity of residual distribution, including checking for outliers. Following the normality assumptions testing methods of Larson-Hall (2015), histograms and p-p plots were charted for each variable. All variables, except inhibitory control and letter writing variables, formed histograms with a normal bell-shaped distribution and a straight line in the p-p plots. Although there was some deviation from normality and homoscedasticity for the inhibitory control and letter writing variables, values of skewness and kurtosis did not exceed the acceptable ranges for normal distributions (Byrne, 2010; George & Mallery, 2016). Acceptable values of skewness fall between − 3 and + 3, and kurtosis is appropriate from a range of − 10 to + 10 (Brown, 2006).

**Table 3** Hierarchical regression analysis predicting reading and spelling score

| | | P1 Reading (N = 883) | | | | P1 Spelling (N = 750) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $\Delta R^2$ | β | *T* | *p* | $\Delta R^2$ | β | *t* | *p* |
| Model 1 | | 0.12 | | | < 0.001 | 0.02 | | | < 0.001 |
| Step 1 | Age (months) | | 0.15 | 4.60** | | | 0.01 | 0.35 | |
| | Maternal education | | 0.32 | 9.99** | | | 0.14 | 3.87** | |
| Model 2 | | 0.11 | | | < 0.001 | 0.01 | | | < 0.001 |
| Step 1 | Age (months) | | 0.05 | 1.66 | | | −0.01 | −0.04 | |
| | Maternal education | | 0.24 | 8.05** | | | 0.12 | 3.32** | |
| Step 2 | K2 non-verbal intelligence | | 0.22 | 6.64** | | | −0.01 | −0.04 | |
| | K2 working memory | | 0.21 | 6.53** | | | 0.11 | 2.75** | |
| | K2 inhibition test (Flanker) | | −0.04 | −1.44 | | | 0.02 | 0.57 | |
| | K1 reading | | 0.03 | 1.12 | | | – | – | |
| | K1 spelling | | – | – | | | −0.01 | −0.21 | |
| Model 3 | | 0.06 | | | < 0.001 | 0.03 | | | < 0.001 |
| Step 1 | Age (months) | | 0.04 | 1.21 | | | −0.01 | −0.39 | |
| | Maternal education | | 0.22 | 7.39** | | | 0.10 | 2.69** | |
| Step 2 | K2 non-verbal intelligence | | 0.17 | 5.45** | | | −0.04 | −0.96 | |
| | K2 working memory | | 0.16 | 5.28** | | | 0.08 | 2.06** | |
| | K2 inhibition test (Flanker) | | −0.02 | −0.61 | | | 0.05 | 1.25 | |
| | K1 reading | | 0.01 | 0.33 | | | – | – | |
| | K1 spelling | | – | – | | | −0.03 | −0.68 | |
| Step 3 | K2 copying geometric shapes (B-3) | | 0.02 | 0.75 | | | 0.07 | 1.76 | |
| | K2 spontaneous drawing (B-4) | | 0.03 | 1.04 | | | 0.03 | 0.79 | |
| | K2 letter-writing (B-7) | | 0.25 | 8.11** | | | 0.17 | 4.41** | |

Statistical significance: $^{**}p < 0.001$; *Model 3*: $F(9, 873) = 40.40$, $p < 0.001$ (Reading); $F(9, 740) = 5.57$, $p < 0.001$ (Spelling)

## Language outcomes

### Reading

The full model was statistically significant, $F(9, 873) = 40.40$, $p < 0.001$, and showed a moderate effect size, $f^2 = 0.08$. This model explained 29.4% of the variance in reading performance. Each block of predictors made a significant contribution to the model (see Table 3). After the first step, controlling for age and mother's education, entry of the cognitive variables and prior literacy scores at step 2 explained an additional 11.4% unique variance in reading performance, $F(6,876) = 44.68$; $p < 0.001$. Entry of the visual-spatial integration predictors in step 3 explained an additional 6% variance in reading performance on top of this. Of the three visual-spatial integration measures, it was only the grapho-motor measure of letter writing that was a significant predictor of reading performance, $\beta = 0.251$, $p < 0.001$.

### Spelling

As with the reading model, the full model was statistically significant, $F(8, 1056) = 8.46$; $p < 0.001$, but the overall effect size was low, $f^2 = 0.03$, and the full model accounted for only 6% of the variance in spelling performance (see Table 3). Each step of the model was significant, and after entry of the block of cognitive variables and prior literacy scores at step 2, the block of visual-spatial integration measures contributed an additional 3% variance, $F(6,743) = 3.381$; $p < 0.001$. Of the three visual-spatial integration predictors, only grapho-motor letter writing was statistically significant, $\beta = 0.17$, $p < 0.001$.

## Discussion

With a large sample of kindergarten children followed longitudinally into the first grade of primary school, the current study replicated prior research within a different cultural context and educational system, and extended the association between grapho-motor skills and reading to beginning spelling skills with grapho-motor subskills. Several studies find that motor skill contributes variance to explaining individual differences in reading. The majority of studies thus far focus on visual-spatial integration and reading. Fewer studies specify grapho-motor skill or investigate their relationship with reading and spelling skills, particularly at the early preschool level.

A first step was to identify *if* the variables (i.e., grapho-motor, reading and spelling) were related. Hence, the current study was designed to validate the international findings of the visual-spatial skills, specifically grapho-motor abilities, and reading pathway within a new sample and to test if this link also exists with spelling. The significance, limitations and future directions arising from this study are discussed below.

### Associations between visual-spatial integration skills and reading and spelling

Overall, the results support the hypothesis that visual-spatial skills, specifically grapho-motor abilities, are related to later literacy achievement. Correlational analyses demonstrated a significant relation between letter writing to reading and to spelling skills. Pearson correlation coefficients between letter writing and reading were similar to, but higher than those reported in previous studies whose average coefficient was 0.30 for fine motor skills. Additionally, examining the longitudinal predictive relations from visual-spatial integration to later reading skills within the large sample lends credence to this interpretation, as discussed next.

### Predictiveness of grapho-motor skills for later reading and spelling achievement

Hierarchical regression analyses that assessed the direct contribution of kindergarten grapho-motor skills to later reading achievement at the beginning of primary school verified the claim that early grapho-motor skills are unique and significant predictors of beginning literacy. The association between letter writing and spelling were also significant, but the effect size was small. This could be attributed to the age of the participants and the difficulty of spelling words. At a young age, it is reasonable that the children may not have developed proper encoding skills needed for the spelling task. Additional skills that were not included in the model may also come into play, such as phonological awareness. This effect, however, was found to be stronger in other scripts, such as in early Chinese writing (Lam & McBride, 2018; McBride-Chang et al., 2011; Wang et al., 2014). Perhaps this is, in part, because there is a heavier requirement on visual-orthographic knowledge necessary for character writing in Chinese, and this seems to play a less significant role in English spelling. Hence, this association needs to be further investigated, to see if the slower developing skills for spelling and writing show a longer-term relation to early fine motor ability. Results from the current study suggest that both reading and spelling outcomes were associated with letter writing, but not with spontaneous drawing or copying geometric shapes in young children.

There are at least two possible reasons for the current lack of association between copying shapes and reading and spelling. First, the age range of participants in the previous study by Carlson et al. (2013) was wide ranging, from 5 to 18 years old. The current study focused on a relatively narrower age range, from 5 to 6 years old. The older participants in Carlson's study would have had a fair amount of experience with print and fine motor experiences like drawing and copying symbols than those in our study. An insightful focus for future literacy research would highlight which types of fine motor practice might be most beneficial at which age for effective transfer to reading and writing skills. The delineation of sub-tests in the current study to separately tap into grapho-motor skill, which is a type of visual-spatial integration, provides further clarity on this issue, and, importantly, considers the relative contribution of the subskills at the beginning of reading acquisition.

These results imply that linguistic skills are especially related to fine motor experiences when children are learning to write English letters versus when they have to draw objects or shapes that have no relation to the script that they are learning in school. This supports Cameron et al.'s (2016) argument that visual-spatial integration and reading are especially related when children are given opportunities to practice writing in their corresponding language rather than simply drawing objects and shapes (Suggate et al., 2018). At a theoretical level, the findings align with the results seen from other past work, suggesting that functionalism could partially support the influence that grapho-motor has on reading and spelling attainment more broadly. Essentially, having greater letter copying skills may facilitate the development of broader cognitive concepts and experiences that would not otherwise be as easily accessed (Iverson, 2010; Suggate et al., 2019). Specifically, children with greater grapho-motor skills may be better equipped than their less dexterous peers to produce or reproduce letters with better accuracy.

Taken at a more general level, copying orthographic symbols could contribute to literacy skills, even when copying unfamiliar scripts. This is especially true with copying Chinese characters or symbols for young Chinese readers (Kalindi et al., 2015). For example, Wang et al. (2015) found that copying of unfamiliar scripts such as Hebrew, Korean and Vietnamese positively correlated with the writing of

Chinese words. Likewise, Lam and McBride (2018) examined copying skills for print written in Vietnamese among Chinese kindergarteners and found that copying characters from foreign languages explained Chinese spelling. Suggate et al. (2019) has addressed the developmental association between the discrete aspect of grapho-motor skill (writing of unfamiliar Greek letters) with both reading and spelling in German at the beginning of literacy acquisition. However, since different cognitive-linguistic correlates were used in the various studies (e.g., non-word repetition versus rapid automatized naming), it is difficult to make direct comparisons across studies and confirm the relationship between copying foreign letters and spelling. Hence, future studies should consider comparing copying of familiar and novel scripts (e.g. English versus Chinese/Arabic/Tamil etc.) in order to determine the best predictor of later reading or spelling achievement.

### Discrepancies in prior literature and resolutions

This study adds to the body of knowledge about the relationship between motor skills and reading and spelling in several ways. First, taking a longitudinal approach, the direction of this relation—from earlier fine motor skills to later literacy skills—could be better understood. The study validates the relationship between visual-spatial integration/grapho-motor and reading skills and extends this link to spelling outcomes. To examine the role of visual-spatial integration on reading and spelling processes, various demographic and cognitive factors were systematically controlled within each step of the hierarchical regression analyses so that the specific contributing effect of each predictor could be analyzed. Thus, the unique contribution of motor skills beyond these controlled variables was shown, and suggests that the fine motor-to-literacy link is not just incidental to working memory, executive function, or nonverbal ability effects. Interestingly, the stronger link of visual-spatial integration was found to reading compared with spelling, although spelling and grapho-motor skills seem to intuitively go together. Given the young age of the sample in this study, this fine motor-to spelling link may just take a longer time developmentally to manifest.

A second contribution of this study is the methodical attempt to isolate the pathway driving the motor-literacy link. Understanding the distinctive contributions of the components (visual-spatial integration as independent from visuo-motor coordination) is essential in addressing the mechanism underlying this link: that is, how different fine motor experiences are associated with literacy skills. For example, in past work (Cameron et al., 2012; Son & Meisels, 2006) that examined the relationship between fine motor skills and reading achievement, it was noted that most studies (with the exception of Carlson et al., 2013; Suggate et al., 2019) combined the effects between these two components. In the current study, visual-spatial integration was isolated, and further divided into tasks measuring specific visual-spatial integration skills—drawing, copying and writing from the IED-III assessment tool—examining these subskills independently in their association with literacy outcomes. Studies on fine motor competency conducted over the past couple of years demonstrate that grapho-motor, visual-spatial integration and visuo-motor coordination appear at different stages of both child and literacy development, and these skills relate to distinct abilities and activities. Given that the skill component of visual-spatial integration is more clearly aligned with developing literacy skills, future studies also should look specifically into visuo-motor coordination (VMC) skills, the other fine motor component that is implicated in the literacy pathway. While visuo-motor coordination skills have been explored more deeply in other languages like German or Chinese, this is not evident in the literature in relation to the English language. In particular, to address what visuo-motor coordination entails and how it connects to visual-spatial integration or grapho-motor and literacy outcomes in English.

Third, this study extends earlier work by Carlson et al. (2013) in selecting a more precise age group to evaluate the visual-spatial integration pathway longitudinally. That is, by focusing on kindergarten children, who are still developing their fine motor skills and linguistic competencies, we have gained a better understanding of early developmental trajectories, and how visual-spatial motor experiences may contribute to literacy outcomes. Additionally, the authors focused on discrete aspects of visual-spatial skills to yield more precise associations between fine motor and reading and spelling skills, extending the work done by Cameron et al. (2012).

The results of the current study contribute to the literature by addressing limitations and inconsistencies associated with the age of the sample. Given that this age group is still developing in terms of their ability to exercise fine motor control, it is commonly reasoned that floor effects might impede the detection of group differences (Cameron et al., 2012). In that view, the observations in the current study were from children aged 6–7 years old and the children were performing reasonably well on all the tasks. Hence, findings from this study refutes such claims by showing that the relationship between visual-spatial integration can be observed among younger children, lending continual support to the validity of the fine motor advantage. Further, given the pertinent role that age plays in such developmental skills, it is within reason for future work to consider placing a greater emphasis on age and fine motor experiences. Hence, extending this research down to an earlier developmental phase with a younger sample of children could provide an initial identification to the association between fine motor experiences and literacy processes.

Furthermore, there is abundant evidence documenting the potential influence of phonological skills in English as well as alphabet knowledge, vocabulary, or rapid automatized naming (RAN) on reading and spelling performance. The relative contributions of these metalinguistic skills and fine motor skills to early reading could be shown for English, as has been done for Chinese (e.g., Kong, 2020; Wang et al., 2015). Specifically, since RAN is considered to be one of the core component skills in learning to read and spell in alphabetic scripts and was revealed as a distinctive correlate of Chinese word reading and spelling (Kong, 2020; Wang et al., 2015), this variable, along with other important predictors of English literacy should be taken into consideration in future studies on fine motor skills' contributions.

## Conclusion

The findings of this study brought confirmation to the interrelationship between fine motor proficiencies and literacy outcomes, generalizing the result to a new cultural context with a Singaporean sample. In line with past work, visual-spatial integration, in particular grapho-motor, is a unique and important pathway to literacy acquisition due to the characteristic effects observed from the motor-linguistic interaction in this study. Across all readers, grapho-motor contributed significant unique variance to both later reading and spelling after controlling for prior literacy skills, cognitive inhibitory control and working memory.

Copying practice facilitates children's internalization of language-related knowledge so that they can develop appropriate writing skills that are reflected in decoding and encoding letters and sounds. The implication for education is that while children enter kindergarten with some pencil operation skills, practicing these grapho-motor skills would be best conducted with corresponding linguistic symbols rather than drawing non-linguistically related objects or shapes. This is because the extent to which a child can achieve automaticity with writing-related tasks may determine the amount of cognitive capacity left unconstrained to focus on other learning objectives, including encoding words for spelling or decoding for reading. In contrast, children who struggle to hold a pencil and who must attend to the specific movements that are needed to form letters will not be expected to progress as quickly in the cognitive tasks of decoding longer words, reading for comprehension and connecting letters with their sounds.

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