Pattern understanding is a predictor of early reading and arithmetic skills

Kelly Burgoyne[1,2]

Stephanie Malone[2]

Arne Lervag[3]

Charles Hulme[4,2]

[1]Division of Human Communication, Development and Hearing, University of Manchester, UK

[2]Learning Sciences Institute Australia, Australian Catholic University, Australia

[3]Department of Education, University of Oslo, Norway

[4]Department of Education, University of Oxford, UK

RUNNING HEAD: Pattern understanding, reading and arithmetic

Total word count: 11907

Declaration of conflicting interests

The authors declare that they have no conflicting interests.

Abstract

There is increasing interest in the role that pattern understanding may play in the development of arithmetic and reading skills. However, longitudinal studies are rare and typically do not control for other predictors which contribute to development in these domains. This large-scale longitudinal study examined the extent to which pattern understanding is a unique predictor of reading and arithmetic, after controlling for a range of theoretically important skills. We assessed a large sample of 5-year old children (*N=569*) in the first few months of school on measures of reading, arithmetic, naming speed, number knowledge, counting, non-symbolic magnitude, executive function, oral language, and non-verbal IQ. Children completed alphanumeric and non-alphanumeric pattern understanding tasks six months later. Reading and arithmetic skills were assessed again 12 months after the initial assessment. Latent variable path models showed that pattern understanding predicted significant additional variance in both reading and arithmetic after controlling for a range of other variables. Pattern understanding was in turn predicted by executive function, which indirectly predicted both reading and arithmetic. Thus, we find support for a role of domain general skills (executive function and pattern understanding) as shared predictors of both reading and arithmetic.

Keywords: arithmetic development, reading development, executive function,
pattern understanding, longitudinal studies

Pattern understanding is a predictor of early reading and arithmetic skills

Introduction

Reading and arithmetic are two fundamental educational skills. Identifying skills at school-entry that predict the development of reading and arithmetic has important implications for both theory and practice. This study examines the role of a relatively little studied skill, pattern understanding, as a foundation for the development of reading and arithmetic in a large-scale longitudinal study of 5- to 6-year-old children.

Pattern understanding and its association with reading and arithmetic

Pattern understanding is the ability to detect the underlying structure in a sequence of colours (e.g., red, red, blue), objects (pen, cup, pen), letters (a, b, b) or numbers (1, 3, 5). It has been argued that pattern understanding is an important component of young children's intellectual development that is particularly relevant to the development of mathematical reasoning (Mulligan & Mitchelmore, 2009; Papic, Mulligan, & Mitchelmore, 2011; Sarama & Clements, 2004; Warren & Cooper, 2006). Whilst this view is not represented in current theoretical models of cognitive development, it appears to be widely accepted in early education practices in which patterning activities regularly feature (Economopoulos, 1998; Rittle-Johnson, Fyfe, Loehr, & Miller, 2015).

There has been a recent upsurge in research on children's pattern understanding. Evidence from this work broadly shows that pattern understanding correlates with concurrent measures of arithmetic (Lee, Ng, Pe, Ang, Hasshim, & Bull, 2012; Lee, Ng, Bull, Pe, & Ho, 2011; VanDerHayden, Broussard, Snyder, George, Meche La Fleur, & Williams, 2011; Warren & Miller, 2013; Schmerold, Bock, Peterson, Leaf, Vennergrund, & Pasnak, 2017; *r's* = .25-.68). In addition, a small number of recent studies demonstrate that pattern understanding is a unique longitudinal predictor of later arithmetic (Nguyen et al., 2016; Rittle-Johnson, Zippert, & Boice, 2019; Rittle-Johnson, Fyfe, Hofer, & Farran, 2017). Rittle-Johnson et al., (2017) report that, in a large sample (*N* = 517) of low-income children, pattern understanding at age 5 years was a unique predictor of mathematical ability at 11 years (β = .08) after controlling for a range of mathematical (non-symbolic and symbolic quantity, counting, calculation and shape knowledge) and cognitive skills (teacher ratings of self-regulation and attention, narrative recall, and letter/word identification).

Fewer studies have examined the relation between pattern understanding and reading. Though there is some evidence to suggest that performance on pattern tasks correlates with measures of reading ability (Bock et al., 2015; Pasnak et al., 2016; Schmerold et al., 2017; *r's* = .20-.33), to our knowledge there are no longitudinal studies that have examined this association. However, a small number of training studies suggest that pattern understanding may be important for both arithmetic and reading development. In these studies, teaching 6-7 year old children to identify patterns leads to gains in both arithmetic and reading (e.g., Kidd et al., 2014; Pasnak, Kidd, Gadzichowski, Gallington, Schmerold, & West, 2015). It is worth noting, however, that in a similar study following the same methodology, Kidd, Carlson, Gadzichowski, Boyer, Gallington, and Pasnak (2013) found that gains following pattern training were specific to arithmetic outcomes; no effect of pattern training was found on measures of reading ability. Thus, at present there is stronger evidence that pattern understanding is related to arithmetic than it is to reading, though evidence for such a connection is beginning to emerge.

Pattern understanding therefore appears related to the development of reading and arithmetic; however, much remains to be understood about the mechanisms underlying this association (see Burgoyne, Witteveen, Tolan, Malone, & Hulme, 2017 for a review). Theoretically, it has been argued that an understanding of patterns allows children to see beyond the concrete properties of discrete items to identify the commonalities (the underlying rule) and make predictions (generalize) from them (Clements & Sarama, 2007; Rittle-Johnson et al., 2017). To the extent that predictable patterns feature in basic principles of mathematics (e.g., counting principles) and literacy (e.g., letter-sound correspondence), a general understanding of patterns may plausibly allow a child to abstract the rules governing number and letter sequences and thereby support the acquisition of arithmetic and reading. In this vein it has been speculated that pattern understanding may be an aspect of some broad, domain-general ability such as fluid intelligence (Pasnak et al., 2016), analogical reasoning (Kidd et al., 2014) or relational thinking (Fyfe, McNeil, & Rittle-Johnson, 2015) which contributes to children's ability to benefit from formal instruction in reading and arithmetic.

Despite these speculations, very little research has examined the cognitive predictors of pattern understanding. To date, these investigations are largely limited to correlational studies which examine the concurrent relations between pattern understanding and aspects of executive functioning (Bennett & Muller, 2010; Bock et al., 2015; Miller, Rittle-Johnson, Loehr, & Fyfe, 2016), relational thinking (Collins & Laski, 2015; Miller et al., 2016), and fluid intelligence (Lee, Ng, Bull, Pe, & Ho, 2011; Lee et al., 2012). Evidence from these studies suggests that pattern understanding correlates significantly with measures that tap aspects of executive function (EF) including cognitive flexibility (also termed 'set shifting' and 'switching'; Bennett & Muller, 2010; Bock et al., 2015; Lee et al., 2012; Miller et al., 2016; Schmerold et al., 2017), and working memory (typically backwards digit span; Lee et al., 2011, 2012; Miller et al., 2016; Schmerold et al., 2017). Pattern understanding correlates with measures of inhibition (Collins & Laski, 2015) though this is not always significant (Lee et al., 2012; Miller et al., 2016; Schmerold et al., 2017). Such inconsistency may be due, at least in part, to the specific task used to measure inhibition. It is also likely to reflect measurement error which can seriously distort the apparent associations between overlapping constructs, especially when reliabilities are imperfect and differ between tasks (Cole & Preacher, 2014).

Measures of fluid intelligence such as Raven's Matrices and performance subtests from the Wechsler intelligence scales (e.g., Block Design) share similarities with some patterning tasks and performance on these tasks correlates with pattern understanding (Lee et al., 2011; 2012). There is evidence from one group, however, that fluid intelligence does not account for unique variance in patterning (Lee et al., 2012) or explain the link between patterning and arithmetic performance (Lee et al., 2011).

It is clear that the cognitive mechanisms which underpin performance on patterning tasks are not well understood (Burgoyne et al., 2017). Further work is needed to examine the extent to which performance on measures of EF and general intelligence predicts performance on pattern understanding tasks, and importantly, whether such measures explain the associations between pattern understanding, reading and arithmetic.

Here we report the first study to examine longitudinal relations between pattern understanding, reading and arithmetic in the same sample. The study addresses three significant limitations of previous work. First, many previous studies have used pattern understanding tasks which include number and letter patterns (e.g., Lee et al., 2011; Pasnak et al., 2016): relations between such measures and arithmetic and reading may plausibly just reflect alphanumeric (letter and number) knowledge. Here we compare pattern understanding tasks which do, or do not, depend on alphanumeric knowledge as predictors of reading and arithmetic. Second, we examine the extent to which a range of cognitive skills predict pattern understanding to elucidate the mechanisms which underpin performance on pattern tasks. Third, it is not yet clear whether pattern understanding is meaningfully separable from other, better established, predictors of reading and arithmetic such as EF. To address these questions we examine the specific role of pattern understanding in the development of reading and arithmetic skills by examining a wide range of other predictors in the same study. Below we consider the evidence for these other predictors.

Other predictors of reading and arithmetic development

Reading and arithmetic skills are highly correlated: arithmetic skills at school entry predict later reading, and early reading predicts later arithmetic ability (Duncan et al., 2007). Furthermore, reading and arithmetic difficulties frequently co-occur in the same child (Jordan, Hanich, & Kaplan, 2003; Landerl, Fussenegger, Moll, & Willburger, 2009). A large-scale ($N = 2586$) population-based study of children in Grade 2 to Grade 4 reported comorbid difficulties with both reading and arithmetic in 25.9% of children (Landerl & Moll, 2010). This evidence raises questions about possible shared cognitive mechanisms underlying both reading and arithmetic development. Pattern understanding may be one such mechanism; however, there are several other skills that may serve as shared or unique predictors of reading and/or arithmetic.

It is well established that in alphabetic languages, variations in learning to read words are predicted by three distinct phonological skills: phoneme awareness, letter knowledge and Rapid Automatized Naming (RAN; Caravolas, Lervåg, Defior, Malkova, & Hulme, 2013; Furnes & Samuelsson, 2011). It has been argued that phonological skills also predict arithmetic (e.g., De Smedt & Boets, 2010; De Smedt, Taylor, Archibald, & Ansari, 2010) but this appears to reflect shared variance with oral language skills. That is, when oral language is controlled, phonological skills predict reading but not arithmetic (Durand, Hulme, Larkin, & Snowling, 2005; Moll, Snowling, Gobel, & Hulme, 2015; Peterson, Boada, McGrath, Willcutt, Olson, & Pennington, 2016; Willcutt et al., 2013).

Compared to reading, less is known about the mechanisms that underpin the development of arithmetic skills. Skills that may form the foundations for arithmetic development include the pre-verbal (non-symbolic) understanding of magnitudes and a range of verbal number skills including counting and knowledge of Arabic numerals. Pre-verbal magnitude understanding is considered to provide an early foundation for the acquisition of spoken number-words and Arabic digits once language is acquired (Dehaene, 1992; von Aster & Shalev, 2007). Verbal-symbolic representations are thought to build on these pre-verbal systems during the pre-school years. However, longitudinal studies with school-age children demonstrate that it is basic verbal number skills which primarily predict arithmetic (e.g., Bartelet, Vaessen, Blomert, & Ansari, 2014; Gobel, Watson, Lervag, & Hulme, 2014; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Moll et al., 2015; Zhang, Rasanen, Koponen, Aunola, Lerkkanen, & Nurmi, 2017).

Impairments on verbally-mediated number tasks may also be found in children with reading difficulties (e.g., Moll, Gobel, & Snowling, 2014; Raddatz, Kuhn, Holling, Moll, & Dobel, 2016) and recent evidence suggests one of these verbal number tasks (counting) predicts both reading and arithmetic fluency (Koponen, Salmi, Eklund, & Aro, 2012; Koponen et al., 2016). In a longitudinal study of 378 kindergarten children, Koponen et al. (2016) found counting independently predicted variance in Grade 1 reading and arithmetic fluency after controlling for phonological awareness, vocabulary, working memory, number concept skills and mothers' education. The connection between counting and reading does not appear to be attributable to problems with basic number processing (Landerl, Bevan, & Butterworth, 2004; Raddatz et al., 2016) but may reflect shared variance with language (phonological and broader oral language skills) and the ability to automatize mappings between verbal and symbolic codes (Moll et al., 2015; Koponen et al., 2016; Purpura, Logan, Hassinger-Das, & Napoli, 2017).

Rapid automatized naming (RAN) assesses children's ability to name a series of pictures, colours, letters or digits as quickly as possible. RAN is a powerful predictor of word-reading skills (Caravolas et al., 2012; 2013) though the association appears to be weaker in the early stages of learning to read than later (Caravolas et al., 2013; Hulme, Nash, Gooch, Lervag, & Snowling, 2015; Hulme & Snowling, 2012). Non-alphanumeric RAN has also been implicated in arithmetic development (Cui, Georgiou, Zhang, Li, Shu, & Zhou, 2017; Donker, Kroesbergen, Slot, Van Viersen, & De Bree, 2016; Koponen et al., 2012, 2016; Zhang et al., 2017). Theoretically, it has been suggested that the connection between RAN and reading may reflect the fact that RAN taps the integrity of a left-hemisphere object naming circuit that is recruited to the task of learning to read (Lervag & Hulme, 2009). Why RAN should contribute to arithmetic development, if it does, is less clear (Cui et al., 2017).

Oral language skills beyond phonology (including vocabulary and grammatical knowledge) are important for the development of reading and arithmetic (Durand et al., 2005; Hulme et al., 2015; Peterson et al., 2016; Purpura et al., 2017; Willcutt et al., 2015). Durand et al. (2005) examined a wide range of cognitive abilities as concurrent predictors of reading and arithmetic in 162 children aged 7 to 10 years. A composite measure of verbal ability (vocabulary, verbal reasoning and listening comprehension) predicted variance in both reading and arithmetic. Recent longitudinal studies provide further evidence that oral language skills play a causal role in the development of reading (Hulme et al., 2015) and arithmetic (Moll et al., 2015). Such studies suggest this association is indirect and mediated by early pre-reading and number skills. That is, good oral language skills in the early years support the acquisition of phonological and verbal number skills which, in turn, predict later outcomes in reading and arithmetic.

Recent evidence also suggests a role for EF as a domain-general predictor of reading and arithmetic development (e.g., Best, Miller, & Naglieri, 2011; Blair & Razza, 2007; Neuenschwander, Rothlisberger, Cimeli, & Roebers, 2012; Willcutt et al., 2013; see Clements, Sarama, & Germeroth, 2016 for a review). For example, a large-scale (*N* = 459) longitudinal study found an EF latent variable (including measures of working memory (WM), inhibition and flexibility) at 7 to 8 years predicted reading and arithmetic achievement 12 months later (Neuenschwander et al., 2012). Other evidence, however, suggests EF is a weaker predictor of reading than arithmetic, with some aspects of EF (particularly WM) being more important than others (see Bull & Lee, 2014). Monette, Bigras, and Guay (2011) assessed 85 children aged 5 to 6 years on multiple measures of WM, flexibility and inhibition and examined these as predictors of reading and arithmetic measured one year later. Only WM had a direct effect and this association was unique to arithmetic; none of the EF measures directly predicted reading (see also Peterson et al., 2016). Further research is needed to clarify these relations while controlling for other well-established cognitive predictors.

Current study

We present the results of a longitudinal study of over 550 children in the early stages of formal education (age 5-6 years) examining the extent to which pattern understanding predicts the development of reading and arithmetic skills after controlling for a wide range of theoretically important predictors. Children were assessed on measures of alphanumeric (letters and numbers) and non-alphanumeric (shapes, colours and objects) pattern understanding, reading, numeracy, RAN, language, and EF. These measures were related to later performance on tests of reading and arithmetic. Based on previous research we predicted that pattern understanding might predict both arithmetic and reading, but hypothesized that the association would be stronger for alphanumeric (i.e., letter and number patterns) than non-alphanumeric patterns. We also predicted that this association might largely be explained by other predictors such as EF.

Method

Participants

This study is part of a longitudinal study conducted in 11 schools in Brisbane, Australia. Ten were fee-paying schools (eight Independent and two Catholic schools); the remaining (state) school was publicly-funded. Government data provides basic demographic information for each school. The Index of Community Socio-Educational Advantage (ICSEA) is a scale that represents levels of educational advantage. Scores on this scale are calculated based on the following formula: ICSEA = SEA (direct/indirect measures of parent occupation and education) + Remoteness + Percent Indigenous student enrolment (Australian Curriculum, Assessment and Reporting Authority, 2013). Values on this scale are assigned at the school-level to reflect the average level of educational advantage for all students in the school. The scale has a median of 1000 (standard deviation = 100) and scores range between 500 (reflecting high levels of educational disadvantage) and 1300 (high levels of educational advantage). Scores that are between 900 and 1100 represent an ‘average’ level of educational advantage. Eight of the participating schools (attended by 81.2% of the sample; *N*=462) had ICSEA values in this range (997 to 1090) and could therefore be considered to serve a student population with an average level of educational advantage. The three remaining schools (serving 107 children i.e., 18.8% of the sample) had higher ICSEA values (values between 1112 and 1153) reflecting a student population with somewhat higher levels of educational advantage (though still levels close to those considered average). In short, the children participating in this study were drawn from schools that might be considered to be in the average range of educational advantage for Australia.

Schools provided informed consent for all children enrolled in the first year of school (Preparatory Year) in January 2016 to participate. All children in the year group took part unless parents opted to withdraw their child. Children were first assessed (time 1; t1) in the first few months of Preparatory Year (between March and June 2016); the t1 sample consisted of 569 children (274 boys; *M* = 63.86 months, range 54 – 82 months, *SD* = 4.36). According to teacher reports, 13.2% of the sample (*N* = 75) were growing up with more than one language in the home. A small number of children (7.7%; *N* = 44) had a diagnosed or suspected learning difficulty (Autism Spectrum Disorder = 15; Speech and Language difficulties = 9; Hearing/Auditory processing problems = 8; Physical development difficulties = 3; Vision problems = 2; No further information = 2; Other = 5).

Subsequent test points were organised so that children were assessed at approximately 6-month intervals. Time 2 data (t2) were collected approximately 6 months after t1 assessments i.e., between September and November 2016 (*n* = 552; *M* = 69.66 months, *SD* = 4.19). Time 3 assessments (t3) were conducted between March and June 2017 at which point children were in Year 1 (*n* = 519, *M* = 75.69 months, *SD* = 4.28). Ethical approval for the study was provided by the Australian Catholic University Human Research Ethics Committee (2015-269H).

Assessments and procedure

As described above, children were assessed at roughly 6-month intervals beginning in the first half of Preparatory Year (t1), with repeat assessments in the second half of Preparatory Year (t2) and the first half of Year 1 (t3). The scope of this longitudinal project was large and consequently many tests were included in the assessment battery. In this article, only the measures related to the aims of the current study are described and analysed. Specifically, at t1 we used data collected on measures of reading and numeracy, RAN, language, and EF. Tests of pattern understanding were only administered at t2. Finally, we used data from measures of arithmetic and reading administered at t3. These measures are described below. Most tests were individually administered with the exception of 4 measures at t1 which were administered as group tasks (whole-class groups); these are number identification, number writing, non-symbolic magnitude understanding and non-verbal IQ.

All testing was conducted in schools. At each test point, the assessments were organised so that children participated in a total of three individual test sessions (conducted 1:1), and three group testing sessions (where tests were administered to whole classes). Individual (1:1) and group test sessions were approximately 20 minutes in length (i.e., 2 hours of testing per child at each test point). Test sessions were organised to contain a balance of tasks measuring the different constructs we were interested in assessing (e.g., reading, arithmetic and EF measures) and the demands placed on the child (i.e., a balance between verbal and non-verbal response tasks). Testing took place in each school over several days at each time point with children completing the different sessions over a number of days. All tests were administered by a member of the research team. The research team consisted of between 4 and 6 testers at any one time. All testers were fully trained in test administration and scoring by senior members of the research team (first and second author).

Time 1 Measures

Early reading

Subtests from the York Assessment of Reading for Comprehension (YARC; Hulme et al., 2012) were used to measure early word reading (EWR), letter-sound knowledge (core test) and phonological awareness (sound deletion). The *EWR* test required children to read a list of single words of increasing difficulty; following 5 consecutive errors the child was asked if they could read any more words on the list before testing was discontinued. *Letter-sound knowledge* assessed children’s ability to provide the sound for printed letters and digraphs. To assess *phonological awareness*, children were asked to delete sounds (syllables and phonemes in initial, final and middle positions) in spoken words. This task was discontinued after 4 consecutive incorrect responses.

Rapid automatized naming (RAN)

RAN was assessed using colour (2 trials) and object (2 trials) naming tasks. Each task contained 5 stimuli (objects: dog, eye, key, lion and table; colours: brown, blue, black, red and green). Children were first asked to name each of the stimuli, with any naming errors corrected. They were then shown an array in which the items were presented 8 times each in a random order and were asked to name them as quickly as possible. The total time taken (in seconds) to name all the items and the number of errors was recorded for each trial. On each trial, a rate score was calculated by dividing the number of objects/colours named correctly (out of 40 items) by the time taken to complete the trial.

Early calculation

Early calculation was assessed using a timed addition task in which children were given 3 minutes to solve up to 10 single-digit addition problems (addends to 10). Problems were presented orally and in print (sums presented vertically) and children responded verbally. Counting objects were available to use as aids.

Number Knowledge

The two number knowledge tasks, numeral identification and numeral writing, were administered as group tests. For *numeral identification*, children were asked to circle one of four printed numbers that matched a spoken number. In the *numeral writing* task children were asked to write six spoken numbers as Arabic numerals (2, 7, 13, 28, 69, and 145). All writing errors (including reversals) were scored as zero.

Counting

Counting was assessed using an object counting task and a rote counting task. *Object counting* required children to count random arrays of an increasing number of objects (9, 14, 23, 36 and 42 objects). Children were awarded a score of 1 for each correct count (i.e., final word in count sequence matched the total number of objects) and a score of 1 for each correct response to the question 'How many are there?' *Rote counting* was assessed by asking children to count aloud to 40; the last number correct in the count sequence was their score.

Non-symbolic magnitude understanding

Non-symbolic magnitude understanding was assessed as a group task. Children were asked to choose one of two surface-area matched dot arrays which contained the highest numerosity (Gobel et al., 2014). Children completed three subtests in a fixed order presenting pairs of numerosities that varied from 6-11 (.86 ratio), 21-45 (.66 ratio) and 5-16 (.57 ratio). Children had 30-seconds per subtest to complete as many items as possible. Although this task differs from typical computerized magnitude comparison tasks, paper-and-pencil based methods have been used successfully in other studies (Nosworthy, Bugden, Archibald, Evans, & Ansari, 2013) and correlations with arithmetic are similar to those reported in meta-analyses of studies typically using computer-presented tasks (Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2017).

Oral Language

Language skills were assessed using a test of listening comprehension, and two subtests from the CELF 4^{AU} measuring Expressive Vocabulary and Sentence Structure (Semel, Wiig, & Secord, 2006). For *Expressive Vocabulary*, children were asked to name pictures of objects or actions. Testing was discontinued after 7 consecutive errors. Each correct response was scored as 0 (incorrect), 1 (partial response) or 2 (correct response). In the *Sentence Structure* test, children chose one of four pictures which matched a spoken sentence. Testing was discontinued following 7 consecutive incorrect responses. *Listening Comprehension* was assessed by asking children to listen to a short story adapted from the YARC (Hulme et al., 2012) and answer 8 related questions.

Executive functioning (EF)

Four measures were included to examine aspects of EF including selective attention, working memory (WM), visual-spatial short-term memory (STM) and inhibition. The tasks used are suitable for children at this age and show moderate stability over time (Gooch, Hulme, Nash, & Snowling, 2014). *Selective attention* was measured using a Visual Search task (Apples Task; Breckenridge, 2008). Children were given 60 seconds to point to red apples within an array containing red apples (targets; n = 30), white apples, and red strawberries (distractors). An efficiency score was calculated using the following formula: targets - distractors/60. *Working memory* was assessed using a backwards word span task in which children repeated increasing lists of words in reverse order. Two trials were presented at each of 8 difficulty levels. Testing was discontinued when the child made an error on both trials within a level. Each correctly recalled list was scored as 1. *Visual-spatial STM* was measured using a dot location task (Cohen, 1997) in which children reproduced a visual pattern of 6 dots after viewing the pattern for 5 seconds (3 learning trials) and after recreating a distractor pattern (1 delayed trial). On each trial, a score of 1 was given to all correctly positioned dots; scores were summed across trials. *Inhibition* was measured using the Heads-Toes-Knees-and-Shoulders Task (HTKS; Burrage et al., 2008). Children were asked to do the opposite of a verbal instruction (e.g., touch their toes when the examiner asks them to touch their head). Two prompts (touch your head/toes) were used for the first ten items (part 1). Children proceeded to part 2 of the test (which used an additional two prompts: touch your shoulders/knees) if they scored 5 or more on part 1. Each item was scored 0 (incorrect), 1 (self-corrected response) or 2 (correct).

Nonverbal IQ

Non-verbal IQ was assessed using an adapted version of the Ravens Coloured Progressive Matrices (Raven, Court, & Raven, 1986) which was administered as a group test.

Children were shown a series of puzzles with a piece missing and were asked to choose one of 6 pieces to complete the puzzle. There were 3 practice trials and 12 test trials.

Time 2 Measures.

Pattern Understanding

We used 3 subtests to distinguish between pattern understanding which relies on alphanumeric knowledge from that which does not: letter patterns (10-items), number patterns (10-items), and non-alphanumeric (shapes, colours, objects; SCO) patterns (20-items). Item descriptions for each of the pattern subtests is provided in Appendix 1. In each subtest, children were shown a 2 dimensional 5-item pattern which followed a predictable repeating or increasing pattern. The final (i.e., fifth) item in each pattern was missing; children were asked to point to one of four alternatives to complete the pattern. Testing on each subtest was discontinued after 4 consecutive incorrect responses. Each correct answer was awarded a score of 1.

Three practice items were administered per subtest to familiarise children with the concept of repeating and increasing patterns. On these items, the experimenter pointed to the pattern items and explained that they made a pattern but the last item was missing. The child was asked to find the item that ‘carries on the pattern’. The experimenter then pointed to each item in the pattern; items were not named but the pattern was emphasised (‘In my pattern there is one (letter), then a different (letter), then the first (letter) again, then the second (letter) again’). The child was then asked to choose the item which ‘carried on’ the pattern. Feedback was given on practice items. For test items, the experimenter highlighted the pattern (‘Here is my pattern’) before asking the child to choose the item that ‘carried on’ the pattern. No feedback was given on test items.

Repeating patterns featured a unit of repeat, starting with simple 2-item repeats (abab) and progressing to 3-item repeats (e.g., aab/abb). Distractors included an incorrect item that appeared in the target pattern, and two additional items that appeared in other test patterns but were not in the target pattern.

Increasing patterns featured sequences of items that increased systematically. Increasing letter patterns were based on the alphabet sequence; number patterns were based on the count sequence. Test items included linear sequences, skip-1, and skip-2 patterns. For increasing non-alphanumeric patterns, items increased in relative size (proportion), in rotation sequence, or in the number of units they contained (unit identification). Distractors included items which appeared earlier or later in the sequence, and items which were visually similar to the correct answer but did not follow the sequence.

Time 3 Measures.

Reading

Reading ability was assessed using measures of single word reading and non-word reading. *Single word reading* was assessed using the EWR (as at t1; Hulme et al., 2012) and the more difficult Single Word Reading Test (SWR; Foster, 2007) which presented a list of single words increasing in difficulty. After 5 consecutive errors, children were asked if they could read any more words listed before discontinuing. *Non-word reading* was assessed using the Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 2012). Children were asked to read as many nonwords as they could in 45 seconds.

Arithmetic

Arithmetic was measured using timed (60 seconds) *addition* and *subtraction* tasks from the Test of Basic Arithmetic and Numeracy Skills (Brigstocke, Moll, & Hulme, 2016). The arithmetic subtests the TOBANS have good reliability (test-retest r = .85 - .93) and correlate highly with the numerical operations subtest of the Wechsler Individual Achievement Test II (r = .81) and school-based measures of achievement (e.g., Maths Standard Attainment Test; r = .72; Brigstocke et al., 2016). For each of the two subtests, children completed three practice questions first. They were then given one minute to answer as many of the 60 test questions as possible. All problems were presented in print, and children gave verbal responses. One point was provided for each correct answer.

Results

Means (standard deviations), maximum scores and reliabilities for all measures are shown in Table 1. Correlations are shown in Table 2 (simple correlations below the diagonal partial correlations controlling for age above the diagonal).

We assessed the longitudinal relations between reading and arithmetic at t3 and key predictors of these skills. Critically, we explored whether pattern understanding at t2 explained additional variance in reading and arithmetic at t3 after accounting for t1 predictors. To do this the latent variable path models shown in Figures 1 and 2 were estimated with Mplus 8.1 (Muthén & Muthén, 1998-2018) with missing values (missing at random) being handled with Full Information Maximum Likelihood estimation. In these models all observed variables are regressed on non-verbal IQ, age and gender. The models reported use Robust Standard Errors (Huber-White Sandwich Estimators) to account for clustering at the school level. The putative cognitive foundations for arithmetic and reading ability are represented by 10 latent variables assessed at t1 (early word reading, phonological awareness, letter-sound knowledge, language, RAN, number knowledge, counting, addition, nonsymbolic magnitude judgement, and executive function (EF)). Four latent variables at t1 (early word reading, phonological awareness, letter sound knowledge, and addition) are defined by just a single measure, with the error variance being estimated from the reliability of the measures.

There are just 2 latent variables at t2 (alphanumeric and non-alphanumeric pattern understanding) and t3 (arithmetic and reading). We deliberately separated alphanumeric pattern understanding (defined by the letters and numbers pattern understanding tasks) from non-alphanumeric pattern understanding (defined by the shapes, colours and objects pattern understanding task) to check that any possible relations between reading and arithmetic and pattern understanding was not simply due to alphanumeric knowledge. For the non-alphanumeric pattern understanding latent variable we used item parcelling (odd versus even items) to produce 2 indicators. The two pattern understanding latent variables were strongly correlated ($r = .62$).

The correlations between all latent variables in this model are shown in Table 3. As expected, all these correlations are positive and statistically significant. In the model shown in Figure 1 all possible predictors of reading and arithmetic were initially included in the model but the nonsignificant regression paths have been deleted from the final models.

The most critical aspects of this model are the predictors of arithmetic and reading. Arithmetic was predicted by addition (t1), number knowledge (t1), and alphanumeric pattern understanding (t2). Reading was predicted by early word reading (t1), phonological awareness (t1), RAN (t1), and alphanumeric pattern understanding (t2). Both alphanumeric and non-alphanumeric pattern understanding (t2) were predicted by EF (t1). Though EF (t1) had no direct effect on arithmetic (t3) there was an indirect effect (EF → alphanumeric pattern understanding → arithmetic) which was significant (standardized indirect effect = 0.188 [95% CI .068, .285]). Similarly, though EF (t1) had no direct effect on reading (t3) there was an indirect effect (EF → alphanumeric pattern understanding → reading) that was significant (standardized indirect effect = 0.136 [95% CI .057, .295]).

Overall, the model (Figure 1) accounted for 77% of the variance in arithmetic and 68% of the variance in reading and provides a good fit to the data (χ^2 (386) = 611.134, $p < .001$; Root Mean Square Error of Approximation (RMSEA) = .033 (90% CI = .028-.038), Comparative Fit Index (CFI) = .97, Tucker-Lewis Index (TLI) = .96).

It is clear that there is a high degree of collinearity between alphanumeric and non-alphanumeric pattern understanding. In the simultaneous regression model shown in Figure 1, non-alphanumeric patterning did not account for any unique variance in reading or arithmetic after accounting for the effects of alphanumeric patterning. To identify whether non-alphanumeric patterning was an important predictor of reading and arithmetic on its own we dropped alphanumeric patterning from the model (see Figure 2). In this model, non-alphanumeric patterning was an important predictor of reading and arithmetic. Reading was predicted by early word reading (t1), phonological awareness (t1), RAN (t1), and non-alphanumeric pattern understanding (t2). Arithmetic was predicted by addition (t1), number knowledge (t1), and non-alphanumeric pattern understanding (t2). Though EF (t1) had no direct effect on arithmetic (t3) there was an indirect effect (EF → non-alphanumeric pattern understanding → arithmetic) which was significant (standardized indirect effect = 0.041 [95% CI .012, .093]). Similarly, though EF (t1) had no direct effect on reading (t3) there was an indirect effect (EF → non-alphanumeric pattern understanding → reading) that was significant (standardized indirect effect = 0.053 [95% CI .026, .091]). Overall, the model in Figure 2 accounted for 68% of the variance in reading and 74% of the variance in arithmetic and provides a good fit to the data (χ^2 (333) = 543.040, $p < .001$; Root Mean Square Error of Approximation (RMSEA) = .034 (90% CI = .029-.040), Comparative Fit Index (CFI) = .97, Tucker-Lewis Index (TLI) = .96).

A number of predictive relations that might have been expected are absent from these models. Language at t1 was not a unique longitudinal predictor of either reading or arithmetic, though the correlations were substantial ($r = .46$ reading, $r = .43$ arithmetic). It is also worth noting that EF and language were strongly correlated at t1 ($r = .68$) and hence share substantial variance. It should also be noted that number knowledge and counting share substantial variance in the models reported, with number knowledge being the stronger predictor (the fact that counting is not a significant predictor of arithmetic reflects the fact that it shares substantial variance with number knowledge). Finally, our study is in line with earlier findings (e.g., Gobel et al., 2014) that nonsymbolic magnitude judgement is not a unique predictor of arithmetic skill after controlling for other relevant predictors, though again these two constructs showed a substantial correlation (*r* = .53).

In summary, these models show that pattern understanding is a predictor of both arithmetic and reading ability after accounting for a range of other potential predictors. This association cannot be explained by alphanumeric knowledge since non-alphanumeric pattern understanding is a significant predictor of reading and arithmetic on its own. The finding that pattern understanding is predicted by EF, and that EF indirectly predicts reading and arithmetic, suggests the relations between pattern understanding, reading and arithmetic may be at least partially explained by EF.

Discussion

This is the first longitudinal study to examine the role of pattern understanding as a predictor of early reading and arithmetic skills. We included a broad range of theoretically important variables in order to examine the specific associations between pattern understanding, reading and arithmetic. One critical aim of the current study was to separate pattern understanding that relies on alphanumeric knowledge (letter and number sequences) from that which does not (patterns that involve colours, shapes and objects). Though there was a strong correlation between these variables (*r* = .62) they could nonetheless be meaningfully distinguished. In line with predictions, pattern understanding was a significant unique predictor of both reading and arithmetic. Importantly, and contrary to predictions, this was not specific to pattern understanding tasks which depended on alphanumeric knowledge but was also significant for non-alphanumeric pattern understanding tasks. EF was a significant predictor of pattern understanding and an indirect predictor of both reading and arithmetic.

The findings from this study are consistent with the view that pattern understanding may play an important role in children's reading and arithmetic development. Only a small number of previous studies have examined the relations between pattern understanding and arithmetic longitudinally (Nguyen et al., 2016; Rittle-Johnson et al., 2017, 2019). It is notable that the bivariate correlations between pattern understanding in Grade 1 and the different arithmetic measures in Grade 5 (r = .31 to .38) reported in Rittle-Johnson et al. (2017) are similar in size to the correlation between non-alphanumeric pattern understanding and arithmetic reported here (r = .39). Our study is the first to examine the longitudinal association between pattern understanding and reading, and our findings make a significant advance upon earlier work in showing that pattern understanding is a longitudinal predictor of both reading and arithmetic ability in the same sample.

It is worth noting here that the pattern understanding tasks used in earlier studies have tended to suffer from low reliability (e.g., Rittle-Johnson et al., 2017; α = .56) and/or floor effects (e.g., Rittle-Johnson et al., 2019) and analyses have not controlled for measurement error. A failure to account for measurement error can seriously distort the pattern of relations in longitudinal studies, especially when predictors differ in their reliability (Cole & Preacher, 2014). Our measures of pattern understanding show moderate to high reliabilities (α = .73-.89) and we have used multiple measures of constructs and latent variables to control for measurement error.

It is not yet clear how or why children's ability to recognise patterns contributes to learning to read and to solve arithmetic problems (Burgoyne et al., 2017). Our findings suggest this is at least partly explained by EF. At present there is no clear consensus on the definition and measurement of EF but three processes have commonly been distinguished (Clements et al., 2016; Miyake et al., 2000; Bull & Lee, 2014): cognitive flexibility, inhibition and working memory (WM). The extent to which these processes are separable in the early years is unclear: WM emerges as a separate factor by the time children start school but inhibition and cognitive flexibility appear to remain undifferentiated until mid-adolescent years (Lee, Bull, & Ho, 2013). Our construct of EF, which included measures of WM, inhibition, visual-spatial short-term memory, and visual attention, appears to have worked well to define a general EF construct in young children

In this study, EF measured at school entry was a direct predictor of pattern understanding measured 6 months later. Our findings complement and extend previous work which demonstrates a link between pattern understanding and EF (Bennett & Muller, 2010; Bock et al., 2015; Collins & Laski, 2015; Lee et al., 2011, 2012; Miller et al., 2016; Schmerold et al., 2017). Pattern understanding tasks therefore may draw upon broader domain-general cognitive processes which govern goal-directed behaviour and attentional control. For example, greater working memory capacity would facilitate children’s ability to process pattern items simultaneously and consider the relations between them. Similarly, inhibition would play a role in children’s capacity to suppress an incorrect response such as one based on an earlier pattern rule.

EF skills also play a role in reading and arithmetic (see Clements et al., 2016), and we predicted that shared demands on EF may account for any connection between pattern understanding, arithmetic and reading. EF was a significant indirect predictor of both reading and arithmetic, via its effects on pattern understanding. Importantly, however, our study shows that pattern understanding predicts unique variance in reading and arithmetic after controlling for the variance that is explained by EF. Arguably, further work is needed with a broader range of EF tasks (e.g., including measures of shifting and cognitive inhibition) to refine our understanding of the structure of EF in young children and explore whether different facets of EF (with possibly different connections to pattern understanding and to reading and arithmetic development) can be reliably differentiated in the age range studied here.

Similarly, as our models controlled for non-verbal IQ, our results cannot be explained by similarities between pattern tasks and measures of fluid intelligence (Pasnak et al., 2016). Thus, there appears to be something specific about understanding patterns that facilitates the development of reading and arithmetic, at least in the early years of formal education. Potentially, the ability to identify patterns reflects the capacity to see beyond the perceptual features of seemingly unrelated stimuli to identify relations between them, recognise underlying rules and regularities and make predictions from them. This understanding could plausibly help children to learn some of the foundational concepts and skills that are important for reading and arithmetic development, such as the associations between spoken and symbolic representations of numbers and letters, the count sequence and word order rules. These are speculations however and it remains a question for further research to elucidate the specific mechanisms which underpin the link between pattern understanding, reading and arithmetic.

Our findings are broadly in line with earlier studies examining the predictors of reading and arithmetic. Reading and arithmetic skills were highly correlated in this sample ($r = .55$ at t1 and .66 at t3) replicating previous work (e.g., Duncan et al., 2007) but they appear to be largely predicted by different skills. Specifically, reading was predicted by phonological awareness and RAN which are consistently strong predictors across previous studies (e.g., Caravolas et al., 2013). That letter-sound knowledge did not emerge as a significant predictor here is explained by its strong correlation with phoneme awareness ($r = .73$). In contrast, arithmetic was predicted by verbal number knowledge (digit identification and number writing). Counting was not a significant predictor of arithmetic which is explained by the high correlation with verbal number knowledge (*r* = .67). Our finding that non-symbolic magnitude understanding was not a significant predictor of arithmetic is consistent with earlier findings (e.g., Gobel et al., 2014) but contrasts with recent meta-analyses that report a significant (albeit weak) association between magnitude understanding and arithmetic (*r'*s = .20 – 24; Chen & Li, 2014; Fazio, Bailey, Thompson, & Siegler, 2014; Schneider et al., 2017). Unlike the current study, however, previous studies have typically not controlled for the wide range of other cognitive predictors of arithmetic considered here.

RAN was a longitudinal correlate of arithmetic (*r* = .55) but was not a unique predictor of arithmetic after controlling for other more powerful predictors. Our findings contrast with those of other work that reports an association between RAN and arithmetic fluency (e.g., Cui et al., 2017; Donker et al., 2016; Koponen et al., 2013, 2016; Zhang et al., 2017). Importantly, the present study includes a wider range of predictors than most previous studies, and the link between RAN and arithmetic was not upheld once other factors were controlled for.

There are a number of limitations to this study which are worth noting here. First, we did not collect detailed information regarding the demographic characteristics of the participating children. Such information would be helpful to examine possible effects of demographic variables such as socio-economic status. Second, we administered our test of pattern understanding at Time 2 when children were in the second half of their first year in school. This design allowed us to examine which of the cognitive skills at school entry were longitudinal predictors of pattern understanding. It should be acknowledged however that this design does not allow us to control for improvements in the other cognitive predictors between Time 1 and Time 2. It would be useful for future studies to measure all predictor variables concurrently.

In conclusion, the findings from this study suggest that pattern understanding is a shared predictor of reading and arithmetic, and that this relation is not dependent on alphanumeric knowledge. One practical implication is that training children to identify patterns may potentially lead to gains in reading and arithmetic. Although this idea has some empirical support (Kidd et al., 2013, 2014; Pasnak et al., 2015) there are methodological issues with this work (Burgoyne et al., 2017) which make it difficult to draw firm conclusions about the benefits of teaching children to identify patterns. Furthermore, recent empirical work suggests that some forms of pattern instruction are more effective than others (Fyfe et al., 2015) and it is clear that important questions about the timing, nature and the content of such teaching remain. For example, given that in this study, alphanumeric pattern understanding is a stronger predictor of reading and arithmetic than non-alphanumeric pattern understanding, should teaching focus on patterns which consist of letters and numbers? Does pattern instruction based solely on non-alphanumeric patterns lead to gains in reading and arithmetic? These questions have important implications both for the teaching of pattern understanding, and for theoretical understanding of the nature of pattern understanding, and should be addressed in future studies. In short, we believe that training studies are needed in order to establish whether the relations identified here between pattern understanding and reading and arithmetic reflect causal effects. If future studies can demonstrate that pattern understanding can be improved by training, and if such training shows transfer to arithmetic and reading, this would have clear implications for theory and for educational policy.

Highlights

- Pattern understanding is a significant longitudinal predictor of early reading and arithmetic skills after controlling for a range of other theoretically important variables
- The association between pattern understanding, reading and arithmetic is independent of alphanumeric skills
- Pattern understanding is predicted by executive function skills which is an indirect predictor of reading and arithmetic

Acknowledgements

This research was supported by a grant from the Australian Catholic University. The authors would like to thank a large team of research assistants and students who assisted with data collection. Particular thanks to the participating schools and children for taking part.

References

Australian Curriculum, Assessment and Reporting Authority (2013). *Guide to understanding 2012 Index of Community Socio-educational Advantage (ICSEA) values.*

Bartelet, D., Vaessen, A., Blomert, L., & Ansari, D. (2014). What basic number processing measures in kindergarten explain unique variability in first-grade arithmetic proficiency? *Journal of Experimental Child Psychology, 117,* 12-28. doi: 10.1016/j.jecp.2013.08.010

Bennett, J., & Muller, U. (2010). The development of flexibility and abstraction in preschool children. *Merrill-Palmer Quarterly, 56*(4), 455-473. doi: 10.1353/mpq.2010.0004

Best, J.R., Miller, P.H., & Naglieri, J.A. (2011). Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. *Learning and Individual Differences, 21,* 327-336. doi: 10.1016/j.lindif.2011.01.007

Blair, C., & Razza, R.P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy skills in kindergarten. *Child Development, 78*, 647-663. doi: 10.1111/j.1467-8624.2007.01019.x

Bock, A., Cartwright, K.B., Gonzalez, C., O'Brien, S., Robinson, M.F., Schmerold, K., Shriver, A., & Pasnak, R. (2015). The role of cognitive flexibility in pattern understanding. *Journal of Education and Human Development, 4, 1,* 19-25. doi: 10.15640/jehd.v4n1a3

Breckenridge, K. (2008, August). *Attention and executive function in Williams syndrome and Down's syndrome.* Paper presented at the Development of Executive Functions Workshop. The University of Oxford, UK.

Brigstocke, S., Moll, K., & Hulme, C. (2016). *Test of Basic Arithmetic and Numeracy Skills.* Oxford: Oxford University Press.

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives, 8, 1,* 36-41. doi: 10.1111/cdep.12059

Burgoyne, K., Witteveen, K., Tolan, A., Malone, S., & Hulme, C. (2017). Pattern understanding: Relationships with arithmetic and reading development. *Child Development Perspectives, 11, 4*, 239-244. doi: 10.1111/cdep.12240

Burrage M.S., Ponitz C.C., McCready E.A., Shah P., Sims B.C., & Jewkes A.M. (2008) Age- and schooling-related effects on executive functions in young children: A natural experiment. *Child Neuropsychology*, *14*, 510–524. doi: 10.1080/09297040701756917.

Caravolas, M., Lervåg, A., Defior, S., Málková, G. S., & Hulme, C. (2013). Different patterns, but equivalent predictors, of growth in reading in consistent and inconsistent orthographies. *Psychological Science, 24*, 1398-1407. doi: 10.1177/0956797612473122

Caravolas, M., Lervåg, A., Mousikou, P., Efrim, C., Litavský, M., Onochie-Quintanilla, E., ... & Seidlová-Málková, G. (2012). Common patterns of prediction of literacy development in different alphabetic orthographies. *Psychological Science, 23*, 678-686 doi: 10.1177/0956797611434536

Chen, Q., & Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: A meta-analysis. *Acta Psychologica, 148,* 163-172. doi: 10.1016/j.actapsy.2014.01.016

Clements, D.H., Sarama, J., & Germeroth, C. (2016). Learning executive function and early mathematics: Directions of causal relations. *Early Childhood Research Quarterly, 36,* 79-90. doi: 10.1016/j.ecresq.2015.12.009

Cohen, M. (1997). *Children's Memory Scale (CMS)*. Pearson.

Cole, D.A., & Preacher, K.J. (2014). Manifest variable path analysis: Potentially serious and misleading consequences due to uncorrected measurement error. *Psychological Methods, 19,* 300-315. doi: 10.1037/a0033805.

Cui, J., Georgiou, G.K., Zhang, Y., Li, Y., Shu, H., & Zhou, X. (2017). Examining the relationship between rapid automatized naming and arithmetic fluency in Chinese kindergarten children. *Journal of Experimental Child Psychology, 154*, 146-163. doi: 10.1016/j.jecp.2016.10.008

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*, 1–42. doi:10.1016/0010-0277(92)90049-N

De Smedt, B., & Boets, B. (2010). Phonological processing and arithmetic fact retrieval: evidence from developmental dyslexia. *Neuropsychologia, 48,* 3973-3981. doi: 10.1016/neuropsychologia.2010.10.018

De Smedt, B., Taylor, J., Archibald, L., & Ansari, D. (2010). How is phonological processing related to individual differences in children's arithmetic skills? *Developmental Science, 13,* 508-520. doi: 10.1111/j.1467-7687.2009.00897.x

Donker, M., Kroesbergen, E., Slot, E., Van Viersen, S., & De Bree, E. (2016). Alphanumeric and non-alphanumeric Rapid Automatized Naming in children with reading and/or spelling difficulties and mathematical difficulties. *Learning and Individual Differences, 47,* 80-87. doi: 10.1016/j.lindif.2015.12.011

Duncan, G.J., Dowsett, C.J., Claessens, A., Magnuson, K., Huston, A.C., Klebanov, P…. & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43,* 1428-1446. doi: 10.1037/0012-1649.43.6.1428

Durand, M., Hulme, C., Larkin, R., & Snowling, M. (2005). The cognitive foundations of reading and arithmetic skills in 7- to 10-year-olds. *Journal of Experimental Child Psychology, 91*, 113-136. doi: 10.1016/j.jecp.2005.01.003

Economopoulos, K. (1998). What comes next? The mathematics of pattern in kindergarten. *Teaching Children Mathematics, 5*, 230-233. doi: 10.1007/BF03217430

Fazio, L. K., Bailey, D. H., Thompson, C. A., & Siegler, R. S. (2014). Relations of different types of numerical magnitude representations to each other and to mathematics achievement. *Journal of Experimental Child Psychology, 123,* 53-72. doi: 10.1016/j.jecp.2014.01.013

Foster, H. (2007). *Single Word Reading Test*. UK: GL Assessment.

Furnes, B., & Samuelsson, S. (2011). Phonological awareness and rapid automatized naming predicting early development in reading and spelling: Results from a cross-linguistic longitudinal study. *Learning and Individual Differences*, *21*, 85-95. doi: 10.1016/j.lindif.2010.10.005

Fyfe, E., McNeil, N.M., & Rittle-Johnson, B. (2015). Easy as ABCABC: Abstract language facilitates performance on a concrete pattern understanding task. *Child Development, 86, 3,* 927-935. doi: 10.1111/cdev.12331

Gobel, S.M., Watson, S.E., Lervag, A., & Hulme, C. (2014). Children's arithmetic development: it is number knowledge, not the approximate number sense, that counts. *Psychological Science, 25, 3,* 789-798. doi: 10.1177/0956797613516471

Gooch, D., Hulme, C., Nash, H.M., & Snowling, M. (2014). Comorbidities in preschool children at family risk of dyslexia. *Journal of Child Psychology and Psychiatry, 55, 3,* 237-246. doi: 10.1111/jcpp.12139.

Hulme, C., Nash, H.M., Gooch, D., Lervag, A., & Snowling, M.J. (2015). The foundations of literacy development in children at familial risk of dyslexia. *Psychological Science, 26,* 12, 1877-1886. doi: 10.1177/0956797615603702

Hulme, C., & Snowling, M.J. (2012) Learning to read: What we know and what we need to understand better. *Child Development Perspectives, 7,* 1-5. doi: 10.1111/cdep.12005

Hulme, C., Stothard, S. E., Clarke, P., Bowyer-Crane, C., Harrington, A., Truelove, E., & Snowling, M. J. (2012). *York Assessment of Reading for Comprehension (YARC): Early Reading – Australian Edition.* London, UK: GL Assessment.

Jordan, N.C., Kaplan, D., Ramineni, C., & Locuniak, M.N. (2009). Early math matters: kindergarten number competence and later mathematics outcomes. *Developmental Psychology, 45,* 850-867. doi: 10.1037/a0014939

Jordan, N.C., Hanich, L.B., & Kaplan, D. (2003). A longitudinal study of mathematical competencies in children with specific mathematics difficulties versus children with comorbid mathematics and reading difficulties. *Child Development, 74, 3,* 834-850.

Kidd, J.K., Pasnak, R., Gadzichowski, M., Gallington, D.A., McKnight, P., Boyer, C.E., & Carlson, A. (2014). Instructing first-grade children on pattern understanding improves reading and mathematics. *Early Education and Development, 25, 1,* 134-151. doi: 10.1080/10409289.2013.794448

Kidd, J.K., Carlson, A.G., Gadzichowski, M., Boyer, C.E., Gallington, D.A., & Pasnak, R. (2013). Effects of pattern understanding instruction on the academic achievement of 1st-Grade children. *Journal of Research in Childhood Education, 27, 2,* 224-238. doi: 10.1080/02568543.2013.766664

Koponen, T., Salmi, P., Torppa, M., Eklund, K., Aro, T., Aro, M., Poikkeus, A-M., Lerkkanen, M-K., & Nurmi, J-E. (2016). Counting and rapid naming predict the fluency of arithmetic and reading skills. *Contemporary Educational Psychology, 44-45,* 83-94. doi: 10.1016/j.cedpsych.2016.02.004

Koponen, T., Salmi, P., Eklund, K., & Aro, T. (2012). Counting and RAN: Predictors of arithmetic calculation and reading fluency. *Journal of Educational Psychology, 105,* 162-175. doi: 10.1037/a0029285

Landerl, K., & Moll, K. (2010). Comorbidity of learning disorders: Prevalence and familial transmission. *Journal of Child Psychology and Psychiatry, 51, 3,* 287-294. doi: 10.1111/j.1469-7610.2009.02164.x

Landerl, K., Fussenegger, B., Moll, K., & Willburger, E. (2009). Dyslexia and dyscalculia: two learning disorders with different cognitive profiles. *Journal of Experimental Child Psychology, 103,* 309-324. doi: 10.1016/j.jecp.2009.03.006

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8- to 9-year old students. *Cognition, 93,* 99-125. doi: 10.1016/j.cognition.2003.11.004

Lee, K., Bull, R., & Ho, R.M.H. (2013). Developmental changes in executive functioning. *Child Development, 84,* 1933-1953. doi: 10.1111/cdev.12096.

Lee, K., Ng, S.F., Pe, M.L., Ang, S.Y., Hasshim, M., & Bull, R. (2012). The cognitive underpinnings of emerging mathematical skills: Executive functioning, patterns, numeracy and arithmetic. *British Journal of Educational Psychology, 82,* 82-99. doi:10.1111/j.2044-8279.2010.02016.x

Lee, K., Ng., S.F., Bull, R., Pe, M.L., & Ho, R. (2011). Are patterns important? An investigation of the relationships between proficiencies in patterns, computation, executive functioning and algebraic word problems. *Journal of Educational Psychology, 103, 2,* 269-281. doi: 10.1037/a0023068

Lervåg A., & Hulme, C. (2009). Rapid naming (RAN) taps a basic constraint on the development of reading fluency. *Psychological Science*, 20, 1040-1048. doi: 10.1111/j.1467-9280.2009.02405.x.

Miller, M.R., Rittle-Johnson, B., Loehr, A., & Fyfe, E.R. (2016). The influence of relational knowledge and executive function on preschoolers' repeating pattern knowledge. *Journal of Cognition and Development, 17, 1,* 85-104. doi: 10.1080/15248372.2015.1023307

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wagner, T.D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49-100. doi: 10.1006/cogp.1999.0734

Moll, K., Gobel, S.M., & Snowling, M.J. (2014). Basic number processing in children with specific learning disorders: comorbidity of reading and mathematics disorders. *Child Neuropsychology,* 1-19. doi: 10.1080/09297049.2014.899570

Moll, K., Snowling, M.J., Gobel, S.M., & Hulme, C. (2015). Early language and executive skills predict variations in number and arithmetic skills in children at family-risk of dyslexia and typically developing controls. *Learning and Instruction, 38,* 53-62. doi: 10.1016/j.learninstruc.2015.03.004

Monette, S., Bigras, M., & Guay, M-C. (2011). The role of executive functions in school achievement at the end of Grade 1. *Journal of Experimental Child Psychology, 109*, 158-173. doi: 10.1016/j.jecp.2011.01.008

Mulligan, J., & Mitchelmore, M. (2009). Awareness of pattern and structure in early mathematical development. *Mathematics Education Research Journal, 21*, 33-49.

Muthén, L. K., & Muthén, B. O. (1998-2015). *Mplus user's guide* (7th ed.). Los Angeles, CA: Muthén & Muthén.

Neuenschwander, R., Rothlisberger, M., Cimeli, P., & Roebers, C.M. (2012). How do different aspects of self-regulation predict successful adaptation to school? *Journal of Experimental Child Psychology, 113,* 353-371. doi: 10.1016/j.jecp.2012.07.004

Nguyen, T., Watts, T.W., Duncan, G.J., Clements, D.H., Sarama, J.S., Wolfe, C., & Spitler, M.E. (2016). Which preschool mathematics competencies are most predictive of fifth grade achievement? *Early Childhood Research Quarterly, 36,* 550-560. doi: 10.1016/j.ecresq.2016.02.003

Nosworthy, N., Bugden, S., Archibald, L., Evans, B., & Ansari, D. (2013). A two-minute paper-and-pencil test of symbolic and non-symbolic numerical magnitude processing explains variability in primary school children's arithmetic competence. *PLoS ONE, 8*, e67918.

Papic, M., Mulligan, J., & Mitchelmore, M. (2011). Assessing the development of pre-schoolers mathematical patterning. *Journal for Research in Mathematics Education, 42,* 237-269. doi: 10.5951/jresematheduc.42.3.0237

Pasnak, R., Schmerold, K.L., Robinson, M.F., Gadzichowski, K.M., Bock, AM., O'Brien, S.E., Kidd, J., & Gallington, D.A. (2016). Understanding number sequences leads to understanding mathematics concepts. *The Journal of Educational Research, 109, 6,* 640-646. doi: 10.1080/00220671.2015.1020911

Pasnak, R., Kidd, J., Gadzichowski, M., Gallington, D.A., Schmerold, K. L., & West, H. (2015). Abstracting sequences: Reasoning that is a key to academic achievement. *The Journal of Genetic Psychology, 176, 3,* 171-193. doi: 10.1080/00221325.2015.1024198

Peterson, R.L., Boada, R., McGrath, L.M., Willcutt, E.G.,, Olson, R., & Pennington, B.F. (2016). Cognitive prediction of reading, math and attention: Shared and unique influences. *Journal of Learning Disabilities,* 1-14. doi: 10.1177/0022219415618500

Purpura, D.J., Logan, J.A.R., Hassinger-Das, B., & Napoli, A.R. (2017). Why do early mathematics skills predict later reading? The role of mathematical language. *Developmental Psychology, 53*, 9, 1633-1642. doi: 10.1037/dev0000375

Raddatz, J., Kuhn, J-T, Holling, H., Moll, K., & Dobel, C. (2016). Comorbidity of arithmetic and reading disorder: Basic number processing and calculation in children with learning impairments. *Journal of Learning Disabilities, 1-11,* doi: 10.1177/0022219415620899

Raven, J. C., Court, J. H., & Raven, J. (1986). *Manual for Raven progressive matrices and vocabulary scales.* London: Lewis.

Rittle-Johnson, B., Zippert, E.L., & Boice, K.L. (2019). The roles of patterning and spatial skills in early mathematics development. *Early Childhood Research Quarterly, 46,* 166-178. doi: 10.1016/j.ecresq.2018.03.006

Rittle-Johnson, B., Fyfe, E.R., Hofer, K.G., & Farran, D.C. (2017). Early Math Trajectories: Low-income children's mathematics knowledge from age 4 to 11. *Child Development,* 88, 5, 1727-1742. doi: 10.1111/cdev.12662.

Rittle-Johnson, B., Fyfe, E.R., Loehr, A.M., & Miller, M.R. (2015). Beyond numeracy in preschool: Adding patterns to the equation. *Early Childhood Research Quarterly, 31,* 101-112. doi: 10.1016/j.ecresq.2015.01.005

Sarama, J., & Clements, D. (2004). Building blocks for early childhood mathematics. *Early Childhood Research Quarterly, 19*, 181-189. doi: 10.1016/j.ecresq.2004.01.014

Schneider, M., Beeres, K., Coban, L., Merz, S., Schmidt, S. S., Stricker, J., & de Smedt, B. (2017). Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: A meta-analysis. *Developmental Science, 20,* 1-16. doi: 10.1111/desc.12372

Schmerold, K., Bock, A., Peterson, M., Leaf, B., Vennergrund, K., & Pasnak, R. (2017). The relations between patterning, executive function, and mathematics. *The Journal of Psychology, 151, 2*, 207-228

Semel, E.,Wiig, E. H., & Secord,W. A. (2006). *Clinical evaluation of language fundamentals, fourth edition — Australian Standardised Edition.* Australia: Pearson Clinical Assessment.

Torgeson, J. K., Wagner, R. K., & Rashotte, C. A. (2012). *Test of Word Reading Efficiency, 2nd edition.* Texas, USA: Pro Ed.

Vanderheyden, A.M., Broussard, C., Snyder, P., George, J., Meche Lafleur, S., & Williams, C. (2011). Measurement of kindergartners' understanding of early mathematical concepts. *School Psychology Review, 40, 2,* 296-306.

von Aster, M.G., & Shalev, R.S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology, 49,* 686-873. doi: 10.1111/j.1469-8749.2007.00868.x

Warren, E., & Cooper, T. (2006). Using repeating patterns explore functional thinking. *Australian Primary Mathematics Classroom, 11,* 9-14.

Warren, E., & Miller, J. (2013). Young Australian indigenous students' effective engagement in mathematics: The role of language, patterns, and structure. *Mathematics Education Research Journal, 25, 1,* 151-171. doi: 10.1007/s13394-013-0068-5

Willcutt, E.G.,, Petrill, S.A., Wu, S., Boada, R., DeFries, J.C., Olson, R.K., & Pennington, B. (2013). Comorbidity between reading disability and math disability: Concurrent psychopathology, functional impairment, and neuropsychological functioning. *Journal of Learning Disabilities, 46, 6,* 500-516. doi: 10.1177/0022219413477476

Zhang, X., Rasanen, P., Koponen, T., Aunola, K., Lerkkanen, M.K., & Nurmi, J.E. (2017). Knowing, applying, and reasoning about arithmetic: Roles of domain-general and numerical skills in multiple domains of arithmetic learning. *Developmental Psychology, 53, 12,* 2304-2318

Table 1.

Means (standard deviations) for all study measures

Time 1 (max. score)	**N**	**Reliability**	**Mean (SD)**
Age (months)	569		63.86 (4.36)
Early Reading			
Early word reading (30)	553	.91	6.60 (6.81)
Letter sound knowledge (17)	557	.91	10.40 (3.83)
Phonological awareness (12)	541	.57	3.56 (2.30)
Naming speed			
RAN Pictures Trial 1	544	.88	0.79 (0.19)
RAN Pictures Trial 2	538		0.74 (0.21)
RAN Colours Trial 1	519	.92	0.70 (0.21)
RAN Colours Trial 2	495		0.65 (0.20)
Early Arithmetic			
Addition (10)	552	.80	4.40 (2.82)
Counting			
Object counting (10)	486	.77	3.09 (1.69)
Rote counting (40)	554	----	28.01 (11.08)
Number Knowledge			
Numeral Identification (14)	537	.60	8.53 (2.33)
Numeral Writing (6)	449	.64	2.43 (1.61)
Non-Symbolic Magnitude Comparison			
SA Ratio .86 (36)	460	----	6.13 (3.55)
SA Ratio .66 (36)	487	----	9.62 (6.07)
SA Ratio .57 (36)	476	----	12.92 (6.49)
Language			
Expressive Vocabulary (54)	546	.80	19.02 (8.37)
Sentence Structure (26)	547	.72	16.16 (4.07)
Listening comprehension (8)	544	.40	2.43 (1.53)
Executive Function			
Selective Attention: Visual Search Efficiency	531	.59 [a]	0.18 (0.10)
Working Memory: Backwards Word Span (16)	556	.45 [a]	3.10 (1.75)
Visual-Spatial STM: Dot Locations (24)	485	.80	17.36 (3.86)
Inhibition: HTKS (40)	547	.79	21.34 (10.06)
Non-Verbal IQ			
Ravens (12)	530	.59	7.17 (2.80)
Time 2			
Pattern understanding			
Shapes, Colours, Objects (20)	524	.89	11.69 (3.91)
Letters (10)	536	.73	4.63 (1.86)
Numbers (10)	531	.81	5.39 (2.10)
Time 3			
Reading			
Early word reading (30)	500	.84	22.23 (6.96)
Single word reading (60)	500	.89	16.52 (9.77)
Nonword reading (66)	468	.85	12.94 (8.94)
Arithmetic			
Addition (120)	490	.92 [a]	11.94 (8.30)
Subtraction (120)	470	.88 [a]	5.66 (4.57)

Note. All reliability values are Cronbach’s alpha unless otherwise stated; [a] stability coefficient (*r*)

Table 2

Correlations Between Measures

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Time 1 Variables																														
1. EWR	-	.74	.49	.38	.43	.34	.32	.40	.25	.40	.42	.35	.19	.26	.26	.26	.22	.12	.18	.23	.24	.33	.21	.23	.29	.59	.69	.63	.45	.38
2. LSK	.71	-	.52	.33	.43	.33	.30	.37	.24	.43	.33	.37	.20	.33	.26	.29	.27	.21	.18	.27	.21	.33	.22	.22	.30	.61	.61	.55	.41	.36
3. SD	.53	.52	-	.23	.32	.25	.27	.28	.22	.28	.23	.28	.24	.21	.22	.29	.27	.07†	.09†	.30	.10†	.24	.15*	.19	.23	.38	.46	.40	.24	.26
4. RAN Pics1	.38	.37	.29	-	.75	.63	.64	.35	.22	.33	.29	.33	.27	.35	.30	.22	.13†	.07†	.29	.25	.16*	.20	.33	.28	.30	.40	.42	.43	.34	.36
5. RAN Pics 2	.40	.42	.32	.79	-	.61	.65	.31	.27	.43	.28	.29	.30	.33	.28	.21	.15*	.06†	.31	.31	.20	.26	.32	.32	.37	.42	.47	.50	.40	.37
6.RAN Col. 1	.33	.33	.27	.64	.65	-	.87	.25	.14*	.25	.38	.30	.26	.22	.23	.12†	.06†	.13*	.19	.22	.18	.14*	.29	.18	.26	.38	.41	.42	.39	.31
7. RAN Col. 2	.29	.30	.25	.64	.64	.86	-	.23	.15	.25	.26	.26	.32	.26	.25	.10†	.09†	.15*	.25	.19	.15*	.11†	.26	.22	.25	.39	.42	.41	.40	.33
8. Addition	.49	.47	.42	.34	.33	.30	.28	-	.24	.36	.23	.21	.25	.35	.26	.22	.29	.11†	.18	.41	.28	.37	.34	.24	.35	.34	.38	.36	.55	.45
9. Object Count	.22	.22	.22	.20	.27	.16	.16	.21	-	.17*	.10†	.23	.17*	.22	.20	.05†	.14*	-.05†	.15*	.12	.09†	.11†	.18	.18	.21	.26	.23	.16	.12†	.17*
10. Rote Count	.40	.42	.32	.29	.32	.25	.25	.37	.26	-	.27	.20	.26	.33	.21	.33	.15*	.17*	.11†	.24	.12†	.31	.31	.28	.29	.46	.43	.34	.29	.30
11. No. Id.	.44	.44	.35	.27	.29	.33	.29	.35	.13	.30	-	.32	.21	.20	.13	.11†	.08†	.03†	.06†	.17*	.17*	.33	.21	.21	.25	.31	.42	.44	.36	.29
12. No. Writing	.36	.38	.29	.24	.26	.25	.23	.25	.17	.21	.33	-	.26	.26	.24	.07†	.11†	.09†	.26	.18	.23*	.14*	.29	.20	.30	.37	.40	.33	.24	.32
13. SA Ratio .86	.24	.27	.33	.25	.27	.26	.29	.33	.20	.29	.25	.20	-	.53	.54	.25	.23	.07†	.10†	.24	.10†	.28	.25	.24	.30	.25	.29	.27	.28	.28
14. SA Ratio .66	.39	.30	.32	.33	.32	.27	.29	.40	.23	.33	.24	.23	.57	-	.55	.18	.27	.17*	.13†	.25	.09†	.28	.33	.30	.41	.36	.31	.29	.39	.38
15. SA Ratio .57	.26	.27	.28	.29	.30	.21	.22	.34	.20	.27	.21	.23	.54	.59	-	.24	.26	.10†	.18	.20	.01†	.22	.26	.25	.30	.27	.28	.24	.33	.32
16. Exp. Vocab	.32	.36	.33	.23	.21	.19	.17	.32	.09*	.35	.26	.09†	.23	.20	.20	-	.39	.30	.06†	.30	.08†	.23	.24	.22	.18	.25	.28	.18	.10†	.13†
17. Sent. Structure	.26	.33	.37	.19	.21	.17	.17	.35	.17	.22	.20	.10*	.29	.30	.25	.45	-	.25	.20	.29	.15*	.28	.29	.28	.16*	.20	.18	.09†	.12†	.13†
18. List. Comp.	.22	.30	.18	.22	.21	.21	.23	.23	.03†	.21	.14	.10*	.13	.19	.17	.40	.33	-	-.01†	.18	.06†	.17*	.13†	.08†	.00†	.08†	.06†	.03†	.11†	.05†
19. Visual Search	.19	.28	.18	.31	.33	.22	.22	.24	.18	.13	.15	.19	.16	.22	.23	.10*	.28	.14	-	.16*	.14*	.09†	.15†	.23	.24	.26	.23	.22	.19	.18
20. Back. Span	.32	.41	.38	.30	.35	.27	.24	.44	.18	.38	.26	.23	.28	.31	.28	.34	.36	.27	.23	-	.19	.25	.34	.20	.31	.29	.31	.32	.29	.31
21. Dot Location	.17	.22	.22	.21	.20	.20	.18	.28	.12*	.13	.17	.18	.19	.16	.12*	.13	.25	.09*	.16	.23	-	.10†	.22	.15	.29	.14*	.12†	.08†	.25	.26
22. HTKS	.39	.44	.40	.30	.31	.27	.20	.46	.18	.32	.31	.18	.35	.38	.31	.32	.34	.22	.23	.43	.23	-	.26	.26	.17*	.20	.25	.25	.26	.25
Time 2 Variables																														
23. Patt. SCO	.28	.34	.26	.28	.29	.25	.20	.36	.16	.31	.26	.23	.26	.29	.26	.27	.31	.15	.28	.37	.23	.31	-	.42	.50	.35	.35	.32	.31	.32
24. Patt. Letters	.30	.33	.26	.21	.26	.17	.19	.32	.12*	.26	.25	.23	.26	.31	.24	.23	.31	.12	.24	.31	.16	.25	.46	-	.41	.38	.34	.28	.23	.29
25. Patt. Numbers	.35	.38	.28	.27	.34	.25	.24	.37	.17	.30	.31	.28	.28	.31	.28	.25	.26	.12	.31	.36	.24	.27	.29	.44	-	.36	.36	.34	.45	.43
Time 3 Variables																														
26. EWR	.56	.65	.43	.39	.42	.34	.34	.39	.23	.47	.37	.40	.28	.36	.32	.32	.31	.20	.29	.41	.17	.36	.39	.41	.42	-	.83	.70	.40	.41
27. SWR	.67	.62	.52	.43	.46	.40	.39	.45	.23	.46	.45	.41	.30	.36	.32	.35	.34	.21	.28	.48	.19	.40	.39	.39	.41	.82	-	.87	.44	.40
28. Non-Word Read	.59	.53	.44	.41	.44	.39	.38	.40	.18	.33	.43	.37	.25	.29	.27	.21	.20	.14	.22	.39	.13	.34	.29	.32	.33	.69	.86	-	.48	.38
29. Addition	.48	.46	.31	.37	.39	.40	.40	.55	.13	.33	.37	.28	.30	.39	.35	.21	.21	.19	.22	.38	.25	.37	.36	.26	.44	.46	.48	.47	-	.61
30. Subtraction	.45	.45	.33	.36	.37	.36	.36	.47	.17	.30	.33	.35	.29	.40	.36	.26	.22	.18	.19	.39	.25	.36	.37	.33	.45	.47	.47	.42	.63	-

Notes. Simple correlations below the diagonal; partial correlations controlling for age above the diagonal. Unless otherwise stated, all correlations are significant at $p<.01$; * $p<.05$; † $p>.05$

Table 3

Correlations among the latent variables in Figure 1

	T1 Read	T1 Sound Del.	T1 LSK	T1 Lang.	T1 RAN	T1 Number Know.	T1 Count	T1 Add	T1 Mag. Comp.	T1 EF	T2 Non-Alpha Patt.	T2 Alpha Patt.	T3 Read	T3 Arith
T1 Read	-	.73	.78	.38	.48	.79	.61	.55	.31	.57	.23	.39	.72	.64
T1 Sound Del.		-	.73	.57	.48	.76	.67	.57	.49	.76	.31	.52	.74	.67
T1 LSK			-	.48	.47	.78	.63	.52	.33	.67	.27	.46	.69	.64
T1 Lang.				-	.36	.35	.57	.47	.38	.68	.28	.46	.46	.43
T1 RAN					-	.66	.55	.44	.41	.63	.26	.43	.55	.55
T1 Number Know.						-	.67	.61	.57	.80	.33	.55	.73	.79
T1 Count							-	.60	.57	.76	.31	.52	.61	.63
T1 Add								-	.49	.74	.30	.51	.54	.72
T1 Mag. Comp.									-	.63	.26	.43	.41	.53
T1 EF										-	.41	.69	.67	.78
T2 Non-Alpha Patt.											-	.62	.38	.39
T2 Alpha Patt.												-	.57	.68
T3 Read													-	.66

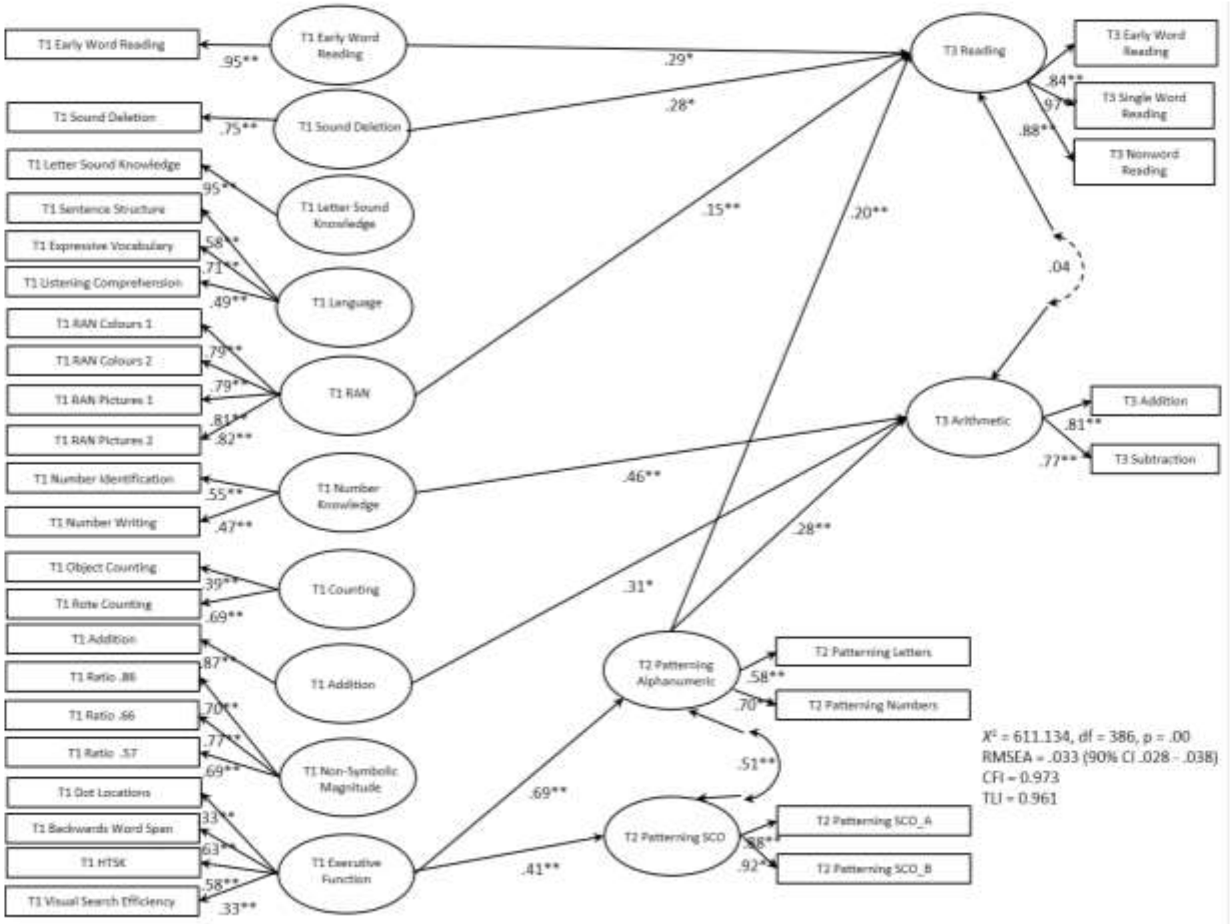

Figure 1. Latent variable path model showing longitudinal predictors of reading and arithmetic. Twin headed arrows represent correlations between variables One headed arrows represent significant regression paths; non-significant paths are not represented. The correlation between the residuals for T1 RAN Colours 1 and 2 (r = 0.67) and T1 RAN Objects 1 and 2 (r = 0.28) are included in the model but not shown in the diagram. All parameters are standardized.

* *p* < .05, ** *p* < .001

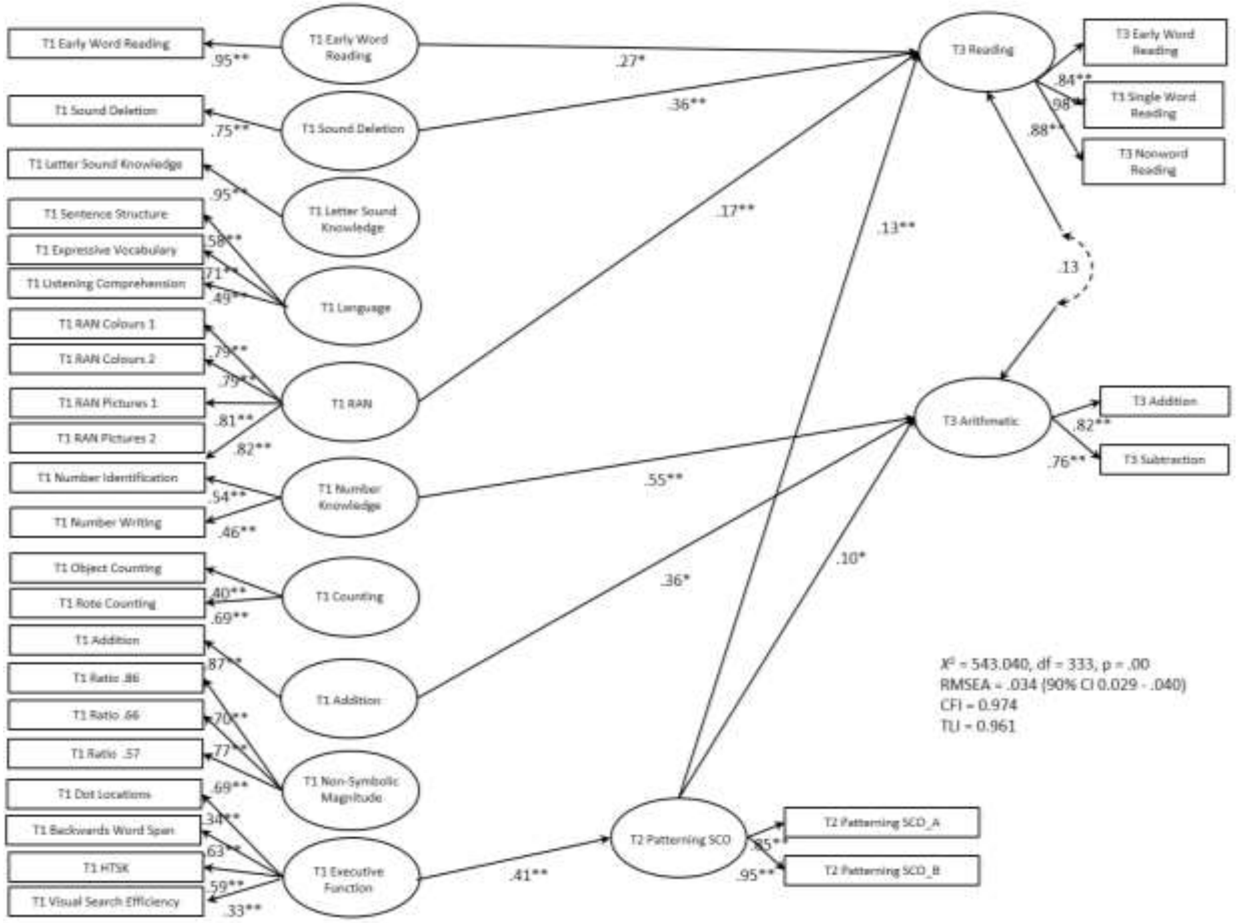

Figure 2. Latent variable path model showing longitudinal predictors of reading and arithmetic. Twin headed arrows represent correlations between variables One headed arrows represent significant regression paths; non-significant paths are not represented. The correlation between the residuals for T1 RAN Colours 1 and 2 (r = 0.67) and T1 RAN Objects 1 and 2 (r = 0.28) are included in the model but not shown in the diagram. All parameters are standardized. * *p* < .05, ** *p* < .001