

Variability in the age of schooling contributes to the link between literacy and numeracy
in Côte d'Ivoire

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Abstract

Literacy and numeracy are correlated throughout development, however our understanding of this relation is limited. We explored the predictors of literacy and numeracy covariance (i.e., shared fluency between literacy and numeracy) in children ($N=1167$, girls=563) in rural Côte d'Ivoire, with specific focus on how developmental timing of instruction may relate to covariance. Many Ivorian children experience late enrollment and grade repetition, leading to variation in age-for-grade; participants were between grades 1 to 6 but their ages ranged from 5 to 15 ($M=9.19$, $SD=2.07$). Phonological awareness, numerical magnitude, ordinality, working memory, and inhibitory control were cognitive predictors of covariance. Age-for-grade was negatively related to covariance suggesting that covariance is related to timing of instruction.

Keywords: literacy, numeracy, age-for-grade

Early numeracy and literacy skills are key indicators of future academic and vocational success (Ritchie & Bates, 2013). However, six out of ten children worldwide fail to acquire basic literacy and numeracy skills even after several years of schooling (UNESCO, 2021). Despite these high global rates of illiteracy and innumeracy, most research on literacy and numeracy acquisition has been conducted in countries with high literacy and numeracy rates. Studies that do investigate low-literacy/numeracy populations typically focus on literacy *or* numeracy (e.g., Jasińska et al., 2019; Piper et al., 2016). However, literacy and numeracy are highly correlated throughout development and many of the same underlying cognitive skills are required for successful development in both domains (Cirino et al., 2018; Duncan et al., 2007; Wolf & McCoy, 2019b). This is clearly illustrated in the literature on learning disorders, where literacy and numeracy deficits co-occur more often than expected based on single-deficit statistics (Landerl & Moll, 2010). By studying these skills within the same study, we can address how these cognitive skills underlie shared fluency in literacy and numeracy.

Multiple cognitive skills (e.g., phonological awareness and working memory) support literacy and numeracy development and their covariance (i.e., shared fluency; Child et al., 2019; Koponen et al., 2020; Korpipää et al., 2017). These cognitive components are dynamic; they develop with age (Gathercole et al., 2004; Mcdowell et al., 2007). Most literacy and numeracy research has been done in the Global North, where most children receive literacy and numeracy instruction at an early age (i.e., begin kindergarten around age 4). However, this developmental trajectory is not globally representative; in low-literacy and low-numeracy populations, children are often old for their grade due to late enrollment or grade repetition (Jasińska et al, in press; Jasińska & Guei, 2022; Sunny et al., 2017; Wils, 2004). Furthermore, in these populations, formal schooling is generally required for literacy and numeracy to develop, as parents often lack

the necessary knowledge and resources to facilitate learning in the home (UNESCO, 2023). At present, we have little to no understanding of how the age at which children receive literacy and numeracy exposure – and correspondingly, the maturity of cognitive components that support literacy and numeracy – may affect shared fluency between literacy and numeracy.

Here, we explore literacy and numeracy covariance in primary school children in rural Côte d'Ivoire. Although policy dictates that children begin school at age 6, Ivorian children enter school anytime between the ages of four and 10 (Jasińska & Guei, 2022). Additionally, children do not always attend school for the entire academic year or enroll every year, leading to increased grade repetition and ultimately larger variation in children's ages (Jasińska & Guei, 2022). Therefore, this population allows us to examine how age-for-grade (i.e., how far a child's age differs from official age for a given grade) is related to literacy and numeracy covariance and its predictors.

The Shared Variance Between Literacy and Numeracy

Literacy and numeracy are complex skills that require integrating multiple core components of cognition. Some of these components are domain-general (e.g., working memory, which supports literacy, numeracy, and a variety of other skills), while others are often considered domain-specific (e.g., phonological awareness, which supports literacy specifically; McClelland et al., 2007; Wagner & Torgesen, 1987). We will specify whether we are referring to domain-specific skills or domain-general skills. However, when referring to both domain-specific and domain-general skills we will use the broader term cognitive skills. Domain-specific literacy skills may be referred to in the literature as preliteracy or language skills, while domain-specific numeracy skills may elsewhere be referred to as early numeracy skills, however for consistency we refer to them only as domain-specific.

According to triangle models of reading, learning to read involves processing semantic (word meaning), phonological (sound), and orthographic (written word) information (Harm & Seidenberg, 2004; Seidenberg, 2005). Skills that assess children's abilities in semantics, phonology, and orthography are predictive of reading ability (Goswami, 2008; Wagner & Torgesen, 1987). For example, phonological awareness (PA) supports learning the spelling-to-sound correspondence that allows successful decoding in early readers (Frost, 1998). PA supports reading throughout development, but more skilled readers can incorporate direct mappings from orthography to semantics (Harm & Seidenberg, 2004). Therefore, while PA and vocabulary are both predictive of reading skill at all stages, PA is more predictive of emergent reading and vocabulary is more predictive of later skilled reading ability (de Jong & van der Leij, 2002; Goswami, 2008; Jasińska & Petitto, 2018; Wagner & Torgesen, 1987). PA and vocabulary are key language skills, support literacy development, and are widely considered domain-specific predictors of literacy.

Numerical skills play a key role in mathematics learning and performance. According to Dehaene's triple-code model, numbers are processed and mentally manipulated as non-verbal quantities (i.e., as objects), as Arabic numerals, and/or verbally as number words (Dehaene & Cohen, 1995). An understanding of magnitude is required to map quantities onto both words and symbols (Malone et al., 2019). Prior research indicates symbolic magnitude (associating quantities and number symbols) and ordinality (understanding the order of numbers) tasks are predictive of arithmetic ability (Goffin & Ansari, 2016; Holloway & Ansari, 2009; Lyons et al., 2014; Schneider et al., 2017). Ordinality and magnitude are key aspects of basic number understanding, required for numeracy to develop, and are widely considered domain-specific predictors of numeracy.

In addition to domain-specific skills, domain-general skills are predictive of both literacy and numeracy (Bosse & Valdois, 2009; McClelland et al., 2007; Savage et al., 2007). Working memory (WM), or one's limited capacity to hold and manipulate information in their mind (Baddeley & Hitch, 1974), is important for both literacy and numeracy because it allows children to hold smaller units of information (e.g., letter sounds or digits) in their minds as they work through more complex tasks (word reading or addition; Savage et al., 2007). Inhibitory control, refers to one's ability to suppress irrelevant or distracting information (Diamond, 2013; Prado et al., 2007). Children's ability to inhibit distracting aspects of their environment or visual stimulus is crucial for literacy and numeracy learning (Blair & Razza, 2007). Both WM and inhibitory control fall under the domain of executive function, defined here as a set of interrelated skills required for self-directed, goal-oriented behaviour (Diamond, 2013). Executive function supports literacy and numeracy, allowing children to attend to relevant information, while inhibiting irrelevant distractions, and mentally represent and manipulate information during classroom learning (McClelland et al., 2007).

If domain-specific skills only predict literacy *or* numeracy, then any relationship between literacy and numeracy can be explained by variability in domain-general skills required for both. However, there is growing evidence that skills that have traditionally been considered domain-specific are also predictive of skills outside of their domain (Lin & Powell, 2022; Purpura et al., 2011; Purpura & Napoli, 2015). For example, both PA and vocabulary are commonly thought of as domain-specific predictors of literacy but have also been found to predict numeracy (Peng et al., 2020; Purpura et al., 2011; Vanbinst et al., 2016). However, previous work has not addressed whether those variables are predictive of literacy and numeracy independently or are predictive

of their shared fluency. By investigating their shared fluency we can understand the cognitive and environmental factors that are predictive of shared fluency between the two skills.

When referring to shared fluency in literacy and numeracy, henceforth covariance, we are interested specifically in whether and how improvement is shared across both skills. The prevailing thought has been that literacy and numeracy development largely rely on distinct underlying skills (e.g., phonological awareness for literacy; number ordering for numeracy), suggesting that literacy and numeracy may improve somewhat independently across development. However, previous research has shown that children similarly improve in literacy and numeracy across development (Duncan et al., 2007). Covariance taps specifically into how improvement is shared, above and beyond the average change in either domain on its own. Although we cannot disentangle coincidental from shared improvement, the extent to which covariance can be predicted by both domain-general and purportedly domain-specific skills, reflects the extent to which improvement is being driven by underlying shared capacity. By understanding how this covariance changes, we can work towards bolstering literacy and numeracy performance simultaneously, rather than focusing on one domain or the other.

Previous work suggests some combination of domain-general and -specific variables predict literacy and numeracy covariance (Child et al., 2019; Cirino et al., 2018; Koponen et al., 2020; Korpipää et al., 2017; Vanbinst et al., 2016). PA, rapid automatized naming, and WM are common predictors of literacy and numeracy covariance (Child et al., 2019; Cirino et al., 2018; Koponen et al., 2020; Korpipää et al., 2017; Vanbinst et al., 2020). Additional, but less frequently researched, predictors of literacy and numeracy covariance include attention (Blair & Razza, 2007), verbal counting (Koponen et al., 2020; Korpipää et al., 2017), numerical

recognition (Cirino et al., 2018; Vanbinst et al., 2020) and numerical magnitude (Koponen et al., 2020).

A longitudinal study investigating domain-general and -specific variables in children when they were in Grade 1 compared to Grade 7 found that rapid automatized naming, letter knowledge, counting sequence, WM, and nonverbal reasoning were time-invariant predictors of literacy and numeracy covariance (Korpipää et al., 2017). In other words, literacy and numeracy covary regardless of the child's age/grade. This is consistent with other studies that suggest literacy and numeracy covariance is not affected by a child's age but remains stable throughout development (Bailey et al., 2020; Koponen et al., 2020; Korpipää et al., 2017). Notably, however, few papers have addressed this question directly and theories such as the bidirectional model, which posits that cognitive predictors and academic skills have bidirectional relationships, suggest covariance should increase with age (Peng & Kievet, 2020). Furthermore, in the Global North, age and grade are highly correlated; children begin school at approximately the same age and advance a grade each year. This is not the case in other parts of the world, where children may not begin school – and therefore literacy and numeracy instruction – until they are 10 to 12 years old or may repeat several grades (Hungu et al., 2014; Jasińska & Guei, 2022). At present, we have little understanding of how different educational trajectories, such as those described above, contribute to literacy and numeracy covariance.

Our exploration of the association between educational trajectories and literacy and numeracy covariance is guided by neoconstructivism, which suggests that new knowledge is built upon existing knowledge (Newcombe, 2011). Cognition develops with age, therefore, if exposure to literacy and numeracy instruction occurs at a later age, their development is occurring with a different existing base of knowledge and cognitive ability. Here, we probe how

developmental timing of instruction may affect literacy, numeracy, and their covariance with the underlying assumption that this relationship may be affected by differences in pre-existing knowledge.

Extant work suggests the cognitive components that predict literacy and numeracy covariance (e.g., WM) develop with age (Child et al., 2019; Gathercole et al., 2004); a 10-year-old will have better WM than a 6-year-old (Gathercole et al., 2004; Pickering, 2001; Towse et al., 1998). A 10-year-old in a Grade 1 class may rely more heavily on their WM as they learn to read than a 6-year-old in that same class because the 10-year-old's WM is more highly developed. The maturity of these cognitive components may affect the degree to which literacy and numeracy are related. In other words, if predictors of literacy and numeracy change based on age of instruction, the predictors of covariance may also change. To date, little theory exists on how or why literacy and numeracy are so highly related; by examining covariance with respect to timing of instruction, we can begin to build a framework within which to understand the relationship between literacy and numeracy.

Environmental Influences on Literacy and Numeracy

In many countries in the Global South, like Côte d'Ivoire, age-for-grade is strongly related to a child's environment (Jasińska & Guei, 2022). The relationship between a child's environment and their age-for-grade, as well as overall academic achievement, can be understood through an ecological systems framework wherein individual, proximal, and distal factors all contribute to a child's development (Bronfenbrenner, 1995). Proximal (i.e., household poverty, low parental education) and distal (i.e., community poverty, school quality) factors contribute to a child's school enrollment or frequency of attendance (Putnick & Bornstein, 2015). For example, a child whose family lives in poverty may participate in labour activities to

support their family, meaning they do not attend school or do so infrequently; this can lead to a student being older than the official age for their grade (Jasińska & Guei, 2022). Proximal factors like socioeconomic status (SES) and family poverty may also affect predictors of literacy and numeracy, such as WM. Research in the Global South shows that low SES is associated with poorer executive functions such as WM and inhibitory control (Jasińska et al., 2022; Khan et al., in prep). Given that executive functions are predictive of literacy and numeracy development (Jasińska et al., 2022; Khan et al., in prep; Wolf & McCoy, 2019b), a population with high levels of child poverty may have poorer executive functions and subsequently lower literacy and numeracy performance.

Parental involvement in children's schooling can also affect the child's literacy and numeracy development. A study in Ghana suggests that caregiver involvement in their child's education mediates the relationship between SES and important predictors of literacy and numeracy (Wolf & McCoy, 2019a). Caregiver participation can be particularly limited in Global South contexts, as parents may not be literate themselves; the adult literacy rate in Côte d'Ivoire is only 47% (UNICEF, 2018). One study of literacy and numeracy covariance found that parental education was predictive of covariance such that greater parental education was associated with higher shared fluency in literacy and numeracy (Korpipää et al., 2017). Taken together, these studies suggest that lower parental literacy and lesser parental involvement in their children's education would be related to lower literacy and numeracy covariance in children.

Rural Ivorian Context

A variety of individual (e.g., age-for-grade), proximal (e.g., parental education), and distal (e.g., community poverty) factors affect learning for Ivorian children. Approximately 30% of the country's population lives in poverty and approximately 38% of children who live in

cocoa-growing areas work in cocoa production; those living in rural communities are overrepresented in these statistics (Sadhu et al., 2020; World Bank, 2021). Poverty and child labour participation impact children's schooling; many do not attend school or do so infrequently. Therefore, there is significant variation in the age at which a child may begin formal education (anywhere between age 4 and age 12) and the consistency with which they attend school (Gulemetova et al., 2016). These factors may lead to poor academic performance and/or grade repetition (Jasińska & Guei, 2022). For example, in Côte d'Ivoire 9.2% of primary school students repeat grades (UNESCO, 2021). Additionally, by the end of primary education, only 8.9% of all students achieve minimum proficiency levels in math and only 10.8% achieve minimum proficiency levels in reading (UNESCO, 2021). School attendance and academic outcomes are even poorer for those in rural communities; rural communities in Côte d'Ivoire have 40% primary school completion rate while urban communities have a 70% completion rate (UNESCO, 2021).

Ivorian children's learning may also be affected by the languages spoken at home and at school. Prior to attending school, children speak one or more Ivorian languages as their mother tongue(s); those in urban areas may have greater exposure to French, but this is less common for those in rural areas. School instruction occurs primarily in French and, for children in deprived rural areas, this is typically when children learn French (Knutsen, 2008). This leads to two important deviations from the majority of existing literature, the first is that these children are learning literacy and numeracy in their second language. Additionally, when the age at which children begin school varies, so does the age at which they are exposed to French.

Current Study

The present study aimed to better understand literacy and numeracy covariance in rural Côte d'Ivoire, where educational context and outcomes differ from those in Global North contexts. Our study investigates the question: What are the predictors of literacy, numeracy, and their covariance? We predicted that literacy, numeracy, and their covariance will be predicted by both domain-general and domain-specific skills. We also explored whether covariance in literacy and numeracy is related to age-for-grade. If covariance is related to age-for-grade, one possible explanation would be that covariance is associated with the maturity of the underlying cognitive components (i.e., domain-general and -specific predictors) at time of instruction. However, if covariance is unrelated to age-for-grade, this would provide evidence that, in line with research in the Global North, covariance is ubiquitous and stable across development. To our knowledge, this important research question has not been addressed previously and has the potential to inform our understanding of the relationship between two key academic skills.

Methods

Participants

Children ($N=1167$, girls=563) between grades 1 to 6 ($Median=3$, $SD=1.54$) and their primary caregivers participated in the study. Participants were children between 5 to 15 years ($M=9.19$, $SD=2.07$) and caregivers were between 17 and 82 years ($M=41.41$, $SD=17.35$). The families were part of a cluster randomized controlled trial of a poverty reduction and education quality intervention in 140 communities in rural Côte d'Ivoire. Within these communities, we collected data from 247 schools and 330 classes. All students were in public schools with monolingual French education programs and followed the national curriculum. For both community and family selection for participation in the randomized controlled trial, see Jasińska

et al., 2021). All data were collected at baseline before the start of any intervention program. Children who were not in primary school (i.e., either in secondary school or not enrolled in school at all) were excluded from these analyses.

While we did not measure pre-primary education in this sample, only approximately 1% of children in rural areas of Cote d'Ivoire attend pre-primary, therefore we have confidence that all or most children begin school in Grade 1 (UNESCO, 2022). This is also the time when children are introduced to written symbols. While in the Global North, children may be exposed to written symbols at home, this is highly unlikely in this population. For example, in our sample less than 30% of families have any books or writing materials in the home (anecdotally, this was most often a bible or other religious text). Additionally, 67% of mothers reported no formal education; of the 33% with formal education experience, 85% of those mothers did not continue past primary school. All schools included in the study are public schools that follow the same curriculum. While the majority of the sample had first exposure to French at school; approximately 0.07% of children reported speaking only French at home and approximately 0.13% were bilingual or multilingual at home including French prior to the start of school.

Measures

Domain-Specific Language and Preliteracy Measures

Phonological Awareness. PA was assessed using two tasks, an initial phoneme elision task (Bruce, 1964) and an initial phoneme identification task (Early Grade Reading Assessment [EGRA]; RTI International, 2015). In the initial phoneme elision task, children were presented with five words and asked to repeat each word while omitting the first phoneme (e.g., 'pomme' [apple] without /p/ is 'om'). In the initial phoneme identification task, children were presented

with three words and asked to identify the initial phoneme in each (the first sound in ‘cheval’ [horse] is /ʃ/). Cronbach’s alpha reliability for phonological awareness was $\alpha = .85$.

Vocabulary. Vocabulary was assessed using an antonym generation task (Woodcock et al., 2001). Children were given five common French words (e.g., ‘content’ [happy]) and asked to provide a word with an opposite meaning (e.g., ‘triste’ [sad]). Cronbach’s alpha reliability was $\alpha = .61$.

Domain-Specific Early Numeracy Measures

Number magnitude and ordinality were assessed using the Early Grade Math Assessment (EGMA; RTI International, 2014).

Number Magnitude. Children were presented with four sets of numbers and were asked to identify the smallest number in each set (e.g., ‘4’ in the ‘4, 8, 9, 7’). Cronbach’s alpha reliability was $\alpha = .85$.

Ordinality. Children were presented with four sets of numbers, in order, and asked to identify the missing number in the set (e.g., ‘13 in ‘11, 12, _’). Cronbach’s alpha reliability was $\alpha = .79$.

Domain-General Measures

Working Memory. Working memory was assessed by measuring backwards digit span (Carlson, 2005). Children were presented with six sets of numbers and asked to repeat the numbers in each set back to the experimenter in inverse order (e.g., set ‘4, 3, 6’ becomes ‘6, 3, 4’). The experimenter marked the correct items. Cronbach’s alpha reliability was $\alpha = .49$.

Inhibitory Control. Inhibitory control was assessed using the Hearts and Flowers task (Diamond et al., 2007). Children were required to press a button depending on whether they were presented with an image of red hearts or flowers. The task typically includes 3 conditions —

congruent, incongruent, and mixed. In the congruent condition, the child was supposed to press the button on the same side as the heart (i.e., if the heart was on the left side of the screen, press the left button). In the incongruent condition, they were instructed to press the button opposite to where the flower appeared. And in the mixed condition, the child was required to alternate between congruent (heart) and incongruent (flower) conditions. Only the mixed condition was included in the present study, children were presented with 13 trials of this condition. Cronbach's alpha was $\alpha = .68$.

Literacy Measures

Literacy was assessed using timed letter and word reading tasks from the French language EGRA (RTI International, 2015) previously used with primary-school children in Côte d'Ivoire (Sobers et al., revise and resubmit; Ball et al., 2022; Jasinska et al., 2022a, b; Jasinska et al., under review). For each task, children practiced first using a small group of sample items and received feedback from the experimenter. After practice, the child was asked to read the task items as quickly and accurately as possible. Experimenters marked incorrect items and terminated the task if the child failed to read the first ten items correctly or after 60 seconds had elapsed. In the letter reading task, children were asked to read 100 letters or combinations of letters (e.g., 'ou'). In the word reading task, children were asked to read 50 familiar French words (e.g., 'bébé', 'fleur'). Cronbach's alpha for these two tasks was $\alpha = .89$.

Letter and word reading, rather than sentence reading, passage reading, or reading comprehension, were chosen because in this population, reading ability is very low (Angrist et al., 2021). More complex measures would have led to larger floor effects; previous work in this population has investigated passage reading and comprehension and found very low scores (Ball

et al., 2022; Jasinska et al., under review). Additionally, using decoding to evaluate reading is in line with other work on literacy and numeracy covariance (e.g., Koponen et al., 2020).

Numeracy Measures

Numeracy was assessed using addition and subtraction tasks from the EGMA (RTI International, 2014). In both tasks, children were instructed to complete the problems as quickly and accurately as possible. Children were told that they could skip over items that they did not know. Experimenters terminated the task after 60 seconds had elapsed and marked the correct items. In the addition task, children were asked to complete 15 single or double-digit addition problems (e.g., $8 + 10$). In the subtraction task, children were asked to complete 15 single or double-digit subtraction problems (e.g., $14 - 3$). Cronbach's alpha for these two tasks was $\alpha = .96$.

Probability of Poverty Index

Probability of Poverty Index (PPI®; Innovations for Poverty Action, 2018) for Côte d'Ivoire was measured. The Côte d'Ivoire poverty scorecard was administered to parents, which asked ten questions about the members of the household and the living conditions (e.g., What is the highest educational level that the head of household has completed?). Parent responses were transformed into a PPI score for the family in accordance with Innovations for Poverty Action's Protocol (Innovations for Poverty Action, 2018). Each score represents the probability of a household being below the National Poverty Line of Côte d'Ivoire. The PPI score was converted into a poverty likelihood percentage using a look-up table. For example, if a family's PPI score is 17, their poverty likelihood percentage would be 75, meaning that the household is 75% likely to be below the National Poverty Line.

Age-for-grade

A child's age-for-grade score measures whether they were in the appropriate grade for their age according to policy (i.e., official age) at the time of data collection. To calculate this measure, we subtracted the official age based on the child's grade from the child's actual age, i.e., an 8 year old child in grade 1 (official age: 6) would have an age-for-grade score of +2 because they were two years older than official age.

Procedure

All data was collected in French. Parents were interviewed and children completed tasks one-on-one with an experimenter who was a native speaker of Ivorian French. Interviews with children took approximately 45 minutes and interviews with parents, which included PPI and a variety of other measures not used here, took approximately 1 hour. Data collection took place in the child's home and each family received a small gift to thank them for their participation. For information on how selected measures were chosen, see Supplementary Materials.

Analysis

Using lavaan (Rosseel, 2012) in R Studio (R Studio Team, 2022), we constructed a structural equation model (SEM) to examine the effects of domain-specific and general skills on literacy and numeracy covariance. We applied the Satorra-Bentler correction (Satorra & Bentler, 1988, 1994) to account for non-normal data (see Table 1). We then used a Multiple Indicators Multiple Causes (MIMIC) model to understand the effects of individual and proximal-level covariates, such as PPI, child's age, and child's age-for-grade on the latent factor of literacy and numeracy covariance (Finch & French, 2015). From this MIMIC model, we can conclude whether differences in literacy and numeracy covariance relate to differences in these environmental factors, in other words, whether the factors influence literacy and numeracy covariance. We then constructed a multi-group SEM in order to determine which predictors, if

any, differed between children who had an age-for-grade score that indicated they were on time as compared to those with an age-for-grade score indicating they were late.

Results

Descriptive Results

Overwhelmingly, scores on literacy and numeracy measures are low (see Table 1). We tested correlations between all measures (see Table 2). Literacy and numeracy measures were positively correlated. Higher age-for-grade was negatively associated with all outcomes except PPI and inhibitory control. PPI was not significantly correlated with any measure. Age and age-for-grade are not correlated, motivating the inclusion of both in structural equation models.

Table 1

Descriptive Statistics

Variable	M	SD	Range	Skew	Kurtosis	Floor Effects (%)	Ceiling Effects (%)
Age	9.19	2.07	5.00 - 15.00	0.54	0.30	-	-
PA	2.68	2.23	0.00 - 8.00	0.64	-0.45	21	3
Vocabulary	2.14	1.28	0.00 - 5.00	-0.07	-0.64	14	2
Magnitude	2.85	1.40	0.00 - 4.00	-0.94	-0.51	27	18
Ordinality	1.92	1.45	0.00 - 4.00	0.00	-1.32	12	47
Inhibitory Control	6.80	2.65	0.00 - 13.00	0.25	-0.09	0.2	3
WM	0.92	0.99	0.00 - 4.00	0.89	0.16	44	0
Letter ID	13.22	15.46	0.00 - 92.00	1.90	4.02	11	0
Word ID	5.82	9.71	0.00 - 48.00	2.41	5.78	47	0
Addition	3.46	3.33	0.00 - 14.00	0.87	-0.24	21	0
Subtraction	2.61	2.68	0.00 - 12.00	1.21	1.06	27	0

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Age-for-grade	0.66	1.65	-5.00 - 5.00	0.57	0.49	-	-
Grade	3.52	1.53	1.00 - 6.00	0.02	-1.03	-	-
PPI Score	56.98	19.27	1.00 - 91.20	-0.78	0.06	-	-

Note. *M* = Mean, *SD* = Standard Deviation

Table 2

Correlation Matrix

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Inhibitory Control	-											
2. WM	0.20*	-										
3. PA	0.28*	0.49*	-									
4. Vocabulary	0.27*	0.26*	0.41*	-								
5. Magnitude	0.22*	0.42*	0.49*	0.33*	-							
6. Ordinality	0.28*	0.50*	0.60*	0.36*	0.61*	-						
7. Letter ID	0.23*	0.40*	0.63*	0.29*	0.44*	0.52*	-					
8. Word ID	0.13*	0.34*	0.55*	0.24*	0.34*	0.44*	0.74*	-				
9. Addition	0.27*	0.52*	0.56*	0.32*	0.54*	0.62*	0.55*	0.49*	-			
10. Subtraction	0.31*	0.47*	0.54*	0.31*	0.44*	0.54*	0.52*	0.47*	0.72*	-		
11. PPI	0.03	-0.04	-0.04	-0.03	-0.02	-0.05	-0.05	-0.05	-0.08	-0.03	-	
12. Age-for-grade	-0.05	-0.18*	-0.24*	-0.14*	-0.26*	-0.25*	-0.22*	-0.20*	-0.25*	-0.22*	0.06	-
13. Age	0.19*	0.29*	0.34*	0.23*	0.40*	0.39*	0.33*	0.29*	0.39*	0.35*	0.03	0.01

Note. * $p < .001$

Structural Equation Models

We constructed a model to examine the predictors of literacy and numeracy separately (see Figure 1A). The model included first-order latent variables of literacy and numeracy using manifest variables of letter and word identification tasks and addition and subtraction tasks, respectively. Domain-general and -specific variables were added to the model as predictors of literacy and numeracy. Individual and proximal factors (i.e., age, age-for-grade, and PPI) were also added as predictors of both literacy and numeracy. The model fit indices suggested a good model fit on several important metrics, see Table 3.

Table 3.

Model fit statistics

Metric of Model Fit	Non-covariance model statistic	Covariance model statistic	Criterion
Robust Chi-Squared	.000(<i>df</i> =19)	.000(<i>df</i> =27)	$p > .05$
Chi-Squared with Satorra-Bentler scaling correction factor	.951	.957	
Robust Root Mean Square of Error Approximation (RMSEA)	0.043	0.060	< 0.06
Robust Standardized Root Mean Square	0.012	0.021	< 0.08
Robust Comparative Fit Index (CFI)	0.988	0.968	≥ 0.95

In line with previous research discussed in the introduction, the non-covariance model demonstrates domain-specific skills are predictive of skills outside of their domain (see Table 4). For example, domain-specific predictors, PA and ordinality, were predictive of both literacy and numeracy. WM, a domain-general skill, was predictive of both literacy and numeracy. Age was

positively related to both literacy and numeracy and age-for-grade was negatively related to both literacy and was negatively associated with numeracy. Taken together, these results motivate examining how these various predictors are related to literacy and numeracy covariance.

Table 4
Results of non-covariance model

Measurement Model		Results	
Latent Variable	Manifest Variable	Std. β	<i>p</i>
Literacy	Letter	0.923	-
	Word	0.806	<.001
Numeracy	Addition	0.888	-
	Subtraction	0.806	<.001

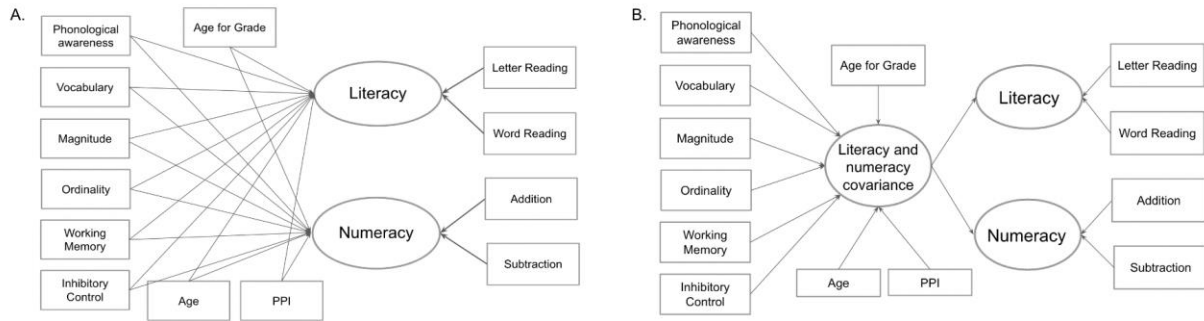
Structural Model			
Regression	Predictor	Std. β	<i>p</i>
Literacy	Phonological Awareness	0.503	<.001
	Vocabulary	-0.017	.508
	Magnitude	0.045	.147
	Ordinality	0.142	<.001
	Working Memory	0.061	.029
	Inhibitory Control	0.010	.696
	Age	0.096	<.001
	Age-for-grade	-0.060	.014
	PPI	-0.026	.271

Numeracy	Phonological Awareness	0.238	<.001
	Vocabulary	0.016	.502
	Magnitude	0.118	<.001
	Ordinality	0.252	<.001
	Working Memory	0.221	<.001
	Inhibitory Control	0.096	<.001
	Age	0.131	<.001
	Age-for-grade	-0.073	.001
	PPI	-0.044	.042

We then constructed a covariance model (see Figure 1B) to examine how predictors affected the relationship between literacy and numeracy. The covariance model included first-order latent variables of literacy and numeracy using the same manifest variables as the non-covariance model. However, this model also included a second-order latent variable of literacy and numeracy covariance. The covariance variable was created out of first-order latent variables of literacy and numeracy and is a measure of how closely related the first-order latent variables are. Both domain-general and domain-specific variables were added to the model as predictors of covariance and, in line with the MIMIC model, individual and proximal factors (i.e., age, age-for-grade, and PPI) were added as predictors at the level of covariance. The model fit indices suggested a good model fit on several important metrics, see Table 2.

Figure 1

Conceptual structural equation models



Note. (A) Conceptual covariance model. (B) Conceptual non-covariance model. Squares indicate manifest variables, and circles indicate latent variables.

In the covariance measurement model, first-order latent variables of literacy and numeracy were measured from their manifest variables and the second-order latent variable was measured from first-order latent variables. All included measures significantly contributed to latent variables and were therefore included in the structural model (see Table 5). In the structural covariance model, phonological awareness was the most significant predictor of covariance and vocabulary was not associated with literacy and numeracy covariance. Numerical magnitude and ordinality were both significant predictors of covariance. Both domain-general variables, WM and inhibitory control, were significant predictors of covariance. We also investigated individual and proximal level predictors of covariance and found both age and age-for-grade were associated with covariance but PPI was not.

Table 5
Results of covariance model

Measurement Model			
Latent Variable	Manifest Variable	Std. β	<i>p</i>
Literacy	Letter	0.932	-
	Word	0.798	<.001
Numeracy	Addition	0.885	-

	Subtraction	0.809	<.001
Covariance	Literacy	0.771	<.001
	Numeracy	0.880	<.001

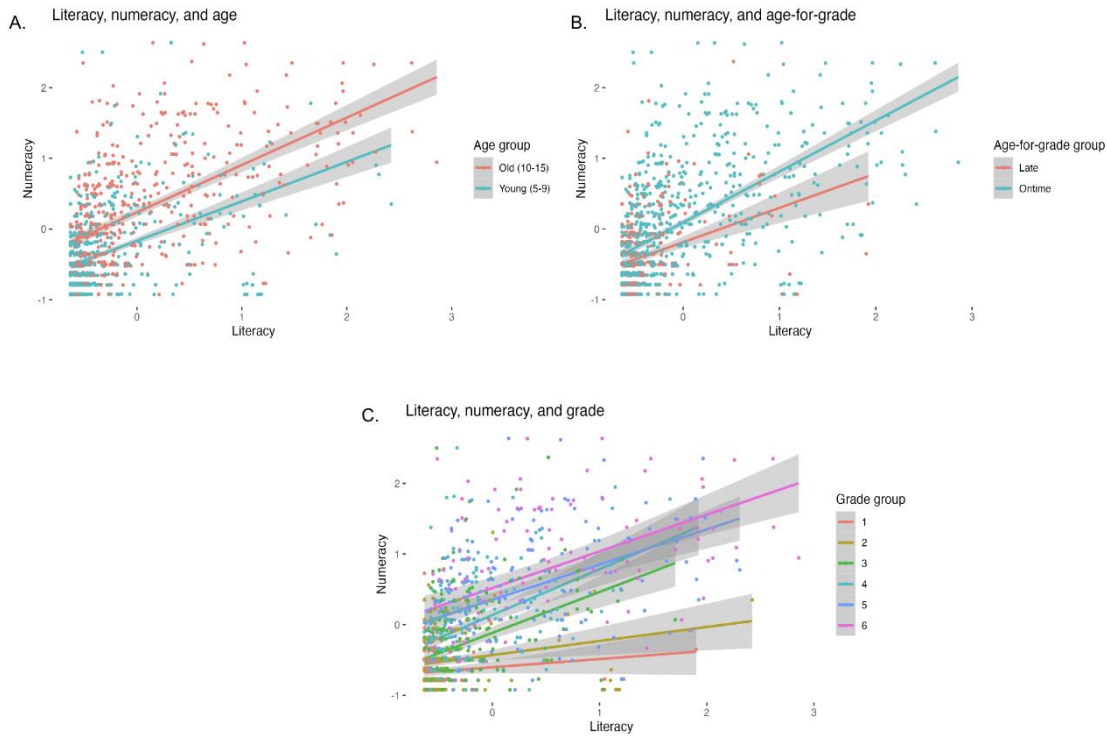
Structural Model

Regression	Predictor	<i>Std. β</i>	<i>p</i>
Covariance	Phonological Awareness	0.412	<.001
	Vocabulary	0.003	.888
	Magnitude	0.106	<.001
	Ordinality	0.248	<.001
	Working Memory	0.187	<.001
	Inhibitory Control	0.075	.001
	Age	0.139	<.001
	Age-for-grade	-0.080	<.001
	PPI	-0.043	.043

In order to better understand the positive association between age and covariance, we visualized the relationship between literacy and numeracy based on important demographic variables (see Figure 2). In all three sub-figures, it is clear that there is a lot of variability in literacy and numeracy performance. Additionally, Figure 2A illustrates age based differences (i.e., older children have better performance), Figure 2B illustrates age-for-grade based

differences (i.e., on-time children have higher performance), and Figure 2C illustrates grade based differences (i.e., children in higher grades have better performance).

Figure 2



Relationships between literacy and numeracy

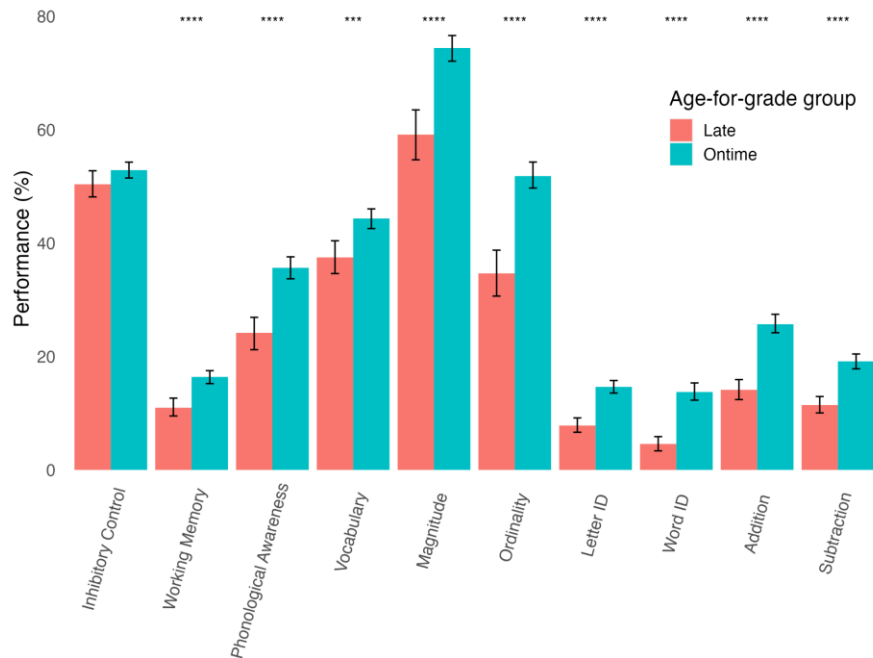
Note. (A) The relationship between literacy and numeracy based on age. (B) The relationship between literacy and numeracy based on age-for-grade. (C) The relationship between literacy and numeracy based on grade.

A finding of particular interest was the negative relationship between age-for-grade and literacy and numeracy covariance. We conducted a multi-group SEM (Feng & Hancock, 2022) to examine potential differences in the predictors of covariance based on age-for-grade. To do so, we transformed the age-for-grade measure into a categorical variable with three levels: early, on-time, and late. We excluded the early group from multi-group analyses due to its small sample size ($n=62$), retaining only the on-time ($n=808$) and late ($n=281$) groups. This additional analysis

allowed us to examine group differences in predictors, otherwise not possible with a MIMIC model. Literacy and numeracy covariance was significant for children in the on-time group but not those in the late group indicating that literacy and numeracy covariance is dependent on age-for-grade. Given that the latent variable of covariance is not significant for the late group, that group model cannot be interpreted further (i.e., there are no significant results in the late group model; but see Supplementary Materials Table A3 for details). We did, however, compare scores between groups using t-tests; we found scores of children in the late group were significantly lower than those for the on-time group for all cognitive measures (see Figure 3). In order to ensure a lack of significance for the late group was not being driven by small sample size, we reran the model with randomly sampled groups of equivalent size from the on-time group. Covariance remained significant in the on-time group regardless of sample size.

Figure 3

On-time vs. Late Scores



Note. Comparing on-time vs. late groups on all cognitive measures. Scores are significantly lower for children in the late group on all measures except inhibitory control. **** $p < .001$, *** $p = .001$

Post-hoc Analyses

To compare predictors for both on-time and late groups, we also conducted a second multi-group SEM wherein we did not include covariance (multi-group non-covariance model). In other words, potential predictors were examined for literacy and numeracy separately (see Table 6). Using this model, we compared the predictors of literacy and numeracy for on-time and late groups. PA and age differentially predicted literacy between the on-time and late groups and there was a marginally statistically significant difference in how PPI predicted literacy between groups.

PA was predictive of literacy in both groups, but significantly more in the on-time group than in the late group. This suggests that PA supports literacy more in children who are on-time for their grade but other skills may support literacy in children who are late for their grade. Notably, even in the late group, PA is the strongest predictor, emphasizing its key role for literacy and numeracy covariance. Age was predictive of literacy in the on-time group but not in the late group. PPI was marginally more predictive of literacy in the late group than the early group, though not significantly predictive in either case. Age differentially predicted numeracy between groups. Age was predictive of numeracy in the on-time group but not in the late group. Working memory was a significant predictor of numeracy in both on-time and late groups, however, was significantly more predictive in the on-time group.

While there are differences between the predictors of on-time and late groups, the majority of the predictors remain the same across age-for-grade groups. This suggests that while

age-for-grade affects performance in the predictors of literacy and numeracy, the predictors themselves do not change.

Table 6
Results of multi-group non-covariance model

Measurement Model		On-time Group (n=808)		Late Group (n=281)		
Latent Variable	Manifest Variable	<i>Std. β</i>	<i>p</i>	<i>Std. β</i>	<i>p</i>	
Literacy	Letter	0.937	-	0.873	-	
	Word	0.820	<.001	0.651	<.001	
Numeracy	Addition	0.886	-	0.816	-	
	Subtraction	0.809	<.001	0.720	<.001	

Structural Model		On-time Group (n=796)		Late Group (n=275)		Difference between groups
Regression	Predictor	<i>Std. β</i>	<i>p</i>	<i>Std. β</i>	<i>p</i>	<i>p</i>
Literacy	Phonological Awareness	0.549	<.001	0.310	<.001	.000
	Vocabulary	-0.011	.708	-0.034	.605	.846
	Magnitude	0.035	.331	0.190	.009	.154
	Ordinality	0.124	.002	0.158	.041	.873
	Working Memory	0.055	.096	0.040	.536	.728
	Inhibitory Control	-0.020	.489	0.079	.203	.149
	Age	0.116	<.001	-0.034	.588	.006
	PPI	-0.036	.180	0.073	.214	.076
Numeracy	Phonological Awareness	0.247	<.001	0.221	.001	.130
	Vocabulary	0.014	.632	-0.000	.995	.745
	Magnitude	0.125	<.001	0.183	.004	.625
	Ordinality	0.236	<.001	0.364	<.001	.981
	Working Memory	0.222	<.001	0.125	.026	.016
	Inhibitory Control	0.085	.002	0.158	.004	.722

Age	0.149	<.001	0.057	.301	.006
PPI	-0.045	.081	0.006	.907	.235

Discussion

Using a series of structural equation models, we investigated the predictors of literacy and numeracy covariance. In line with our prediction, we find that domain-general and -specific skills are predictive of both literacy and numeracy performance. We also find literacy and numeracy covary for children in the on-time group (i.e., children in the correct grade based on official age), and for this group, both domain-general and -specific skills are predictive of covariance. No significant covariance between literacy and numeracy was observed for children who are older for their grade. Taken together, we find that literacy, numeracy, and their covariance are negatively related to age-for-grade. This suggests that developmental timing of instruction affects the relationship between literacy and numeracy.

Predictors of Covariance

The covariance model demonstrated that literacy and numeracy covary in children in Côte d'Ivoire and that both domain-general (WM and inhibitory control) and domain-specific (PA, numerical magnitude, and numerical ordinality) skills are predictive of literacy and numeracy covariance. PA was the strongest predictor of covariance, in line with previous research, which has identified PA as a predictor of literacy (Goswami, 2008; Jasińska & Petitto, 2018; Wagner & Torgesen, 1987), numeracy (Vanbinst et al., 2016), and literacy and numeracy covariance (Koponen et al., 2020). Numerical magnitude and ordinality, typically considered domain-specific predictors of numeracy, were also predictive of covariance. Magnitude has been cited as predictive of covariance in other studies, with evidence suggesting this effect is independent of visual processing (Cirino et al., 2018; Koponen et al., 2020). To our knowledge, ordinality, as it relates to covariance, has not been addressed previously. Domain-general

variables (WM and inhibitory control) have previously been reported to predict covariance (Blair & Razza, 2007; Koponen et al., 2020). Our results corroborate previous work that suggests that variables that are typically considered to be domain-specific predictors of literacy or numeracy are predictive outside of their domain (Koponen et al., 2020). Furthermore, our findings suggest that, despite the vast differences in individual, proximal, and distal factors between the Global North and Global South, the predictors of covariance largely remain the same for children who begin school on time.

Previous work has found a significant positive relationship between parental education and literacy and numeracy covariance (Koponen et al., 2020; Korpipää et al., 2017). We found no effect of PPI – which includes parental education – on literacy and numeracy covariance. We first thought the lack of significant findings may be due to overlap with age-for-grade, as children of families with higher PPI are often old for their grade, however, there was no significant correlation between age-for-grade and PPI in our study. Participants were part of a larger intervention study in which economically vulnerable families were specifically targeted. Therefore, while there was variability in PPI in our sample, it is possible that our lack of significant PPI finding is due to all participants being above a certain PPI threshold. In other words, PPI scores could have been high enough that all children were similarly disadvantaged.

Vocabulary

One notable finding within the current work is the insignificant effect of vocabulary. In the current study, vocabulary was not predictive of literacy, contrary to previous work in Côte d'Ivoire using the same task (Sobers et al., revise and resubmit). The vocabulary measure, an antonym generation task, consisted of 5 items ($\alpha = .61$) and had comparable reliability to a 10-item version (previously used with primary school children in Côte d'Ivoire ($\alpha = .63$)). Vocabulary

is a robust predictor of literacy in general (de Jong & van der Leij, 2009) and this specific task has been found to predict literacy in this population (Ball et al., 2022; Jasińska et al., 2022). We have investigated the reliability and validity of language and literacy tasks in this population in a separate manuscript (Sobers et al., revise and resubmit). We found the 10-item version of the task was fairly reliable ($\alpha = .63$) and valid (i.e., correlated with other language measures and predicted reading performance); we also replicated the analysis with a 5-item version and found similar reliability and validity (see osf.io/wgsud). While vocabulary has been found to predict literacy and numeracy separately in previous research, the existing literature does not address whether it is predictive of covariance. Based on our work, vocabulary was not a significant predictor of covariance. That said, we recommend further investigation using additional measures of vocabulary to probe the association between vocabulary and covariance further.

Age

In the covariance model, age uniquely predicted covariance. Older age was associated with greater shared literacy and numeracy fluency. This is contrary to some previous work that has found no relationship between the two variables; that is, literacy and numeracy covary regardless of age (Koponen et al., 2020). Additional research is required to understand why findings in Côte d'Ivoire differ from those in Global North contexts and what environmental factors may play a role in these differences. These findings can be understood within a bidirectionality perspective and the theory of mutualism, which assumes bidirectional relations between skills and abilities due to mutually beneficial interactions (Peng & Kieviet, 2020). In this case, that refers to bidirectionality between cognitive skills (e.g., working memory) academic outcomes (e.g., literacy and numeracy). In other words, as your cognitive skills improve so will your academic outcomes so vice versa. There is evidence to suggest that relations between these

skills increase with age (but see Peng & Kievet, 2020 for details). We posit that bidirectionality, and subsequently age-related increase in covariance, may characterize the relationship between covariance and its predictors observed in the current study and align with our findings that covariance increases with age.

Age-for-grade

Age-for-grade was associated with lower covariance; put another way, the older a child was for their grade, the lower the shared fluency between their literacy and numeracy skills. To further probe the effects of age-for-grade on covariance, we compared on-time and late students in a multi-group covariance model. We found significant covariance between literacy and numeracy in students in the on-time group but not those in the late group. Children who begin formal literacy and numeracy instruction earlier show greater covariance between the two skills compared to students who begin formal instruction at an older age.

We posit that this difference in covariance between on-time and late students is, at least in part, to the key role of PA in literacy and numeracy covariance. Early-life exposure to a language is critical to mastering its phonology (Werker et al., 1981; Werker & Tees, 2004). Children in rural Côte d'Ivoire commonly speak one of ~60 Ivorian languages at home, and first begin learning French (the language of literacy and school instruction) at school. Children who enrolled in school at a later age (and are old for their grade) also started learning French at a later age (Knutsen, 2008). Older age of French language exposure means poorer phonological sensitivity and poorer PA. PA is the greatest predictor of covariance, therefore, poorer PA could lead to decreased covariance. In line with our interpretation that sensitive periods for phonology may underlie differences between on-time and late students, PA was more predictive of literacy in on-time students than late students.

Age-for-grade is an informative measure with the potential to capture the cumulative influence of multiple aspects of a child's environment that contribute to late school enrollment and grade repetition (e.g., poverty, parental education). However, we were unable to disambiguate the unique effects of age of enrollment and grade repetition, both of which contribute to a child being older for their grade. Investigating the unique effects of age of enrollment and grade repetition would further inform theories of literacy and numeracy covariance.

Limitations and Future Directions

Our study suggests that literacy and numeracy and their covariance are related, at least in part, to the timing of formal literacy and numeracy instruction across developmental sensitive periods. Additional research in the Global South will allow for the examination of whether these findings are ubiquitous or specific to Côte d'Ivoire. Our sample consisted of families from rural Côte d'Ivoire, where environmental and educational factors differ significantly from urban areas. Additionally, these families were all part of cocoa-farming co-operatives, therefore, the sample is not representative of all children in rural Côte d'Ivoire. Future research would benefit from understanding how specific environmental factors (e.g., urban vs. rural) affect literacy and numeracy development and their covariance.

All data was collected in the participants' second language, French. This represents a major deviation from all previous research on literacy and numeracy covariance as well as a potential limitation of the current study. Unfortunately, due to a lack of suitable measures, we were unable to address how first and second language skills may differentially predict covariance. In our sample, participants have a wide variety (20+) of home languages. Not only would it have been difficult to have available testers in all languages, but currently language

measures only exist in four of these languages (see Jasińska et al., 2022 for the development of these measures). Furthermore, many of these languages do not have writing systems, or at least do not appear in written forms in rural contexts, so our other measures would not be able to be adapted to local languages. This is one of the major challenges of conducting research in countries with large variation in languages and many languages without writing systems. However, one possible avenue for future research would be to explore how multilingualism is, if at all, related to literacy and numeracy covariance in populations where local language measures are available.

Another factor that must be considered when interpreting the current results is the presence of large floor effects for some of the included measures. It is possible that lack of significant covariance in the high age-for-grade group may be related to the presence of large floor effects and subsequent lack of variability in measures for children in this group. Unfortunately, we did not have the statistical power to conduct additional analyses that assess floor effects directly in the current study. The presence of large floor effects is an additional challenge that comes with research in low-literacy and low-numeracy contexts. Despite using existing assessments of literacy and numeracy (e.g., letter identification, single digit addition), many of the children in this sample were not able to complete the tasks. Finally, it is important to note that the current work is cross-sectional in nature, however, future work would also benefit from investigating these relationships longitudinally.

Implications and Conclusion

Our work sheds light on the relationship between literacy and numeracy; we corroborate previous research that suggests that literacy and numeracy covariance is predicted by both domain-general and domain-specific predictors. These findings are distinct from literature that

examines literacy and numeracy separately, as they allow us to address whether the predictors of both literacy and numeracy are due to shared processes, or associated with literacy and numeracy differentially.

Furthermore, this study provides insight into how cognition underpins learning; our findings suggest that the developmental timing of educational experiences is related to literacy and numeracy covariance. We found evidence that suggests that covariance occurs for children who begin school on time and progress each year. Rooted in neoconstructivism, we propose these differences may be related to the maturity of supporting cognitive components at time of instruction. Neoconstructivism takes into account that cognitive development is contingent upon existing knowledge at the time when learning occurs (Newcombe, 2011). If children are being exposed to literacy and numeracy at an older age, their development of literacy and numeracy skills, and the degree to which those skills are related may be affected. That said, our data and analyses do not address the question of maturity directly and future work is certainly required in order to distinguish this theory from other possible explanations.

Importantly, research conducted in the Global North is not able to capture the nuance of how timing of education (and subsequent maturity of underlying cognitive components) is related to literacy and numeracy, as there is little variance in the timing of children's literacy and numeracy instruction. We emphasize the need for further research to understand literacy and numeracy in the Global South. When research focuses primarily on the Global North, we exclude the majority of the world's population and limit our understanding of literacy and numeracy development to a specific set of environmental factors. Research that is globally representative of literacy and numeracy (as well as their covariance) is imperative.

We investigated a population with low literacy and numeracy rates; to improve literacy

and numeracy globally, we must understand development in these vulnerable populations. To that point, our results have practical implications. Poorer performance in literacy and numeracy was associated with increased age-for-grade, therefore, improving literacy and numeracy rates requires ensuring that children enroll in school on time and progress each year. Ivorian policy indicates that children should begin school at age six; however, systemic disadvantages at every level (e.g., child labour, poverty, parental education) lead to late enrollment, decreased attendance, and grade repetition. We stress that policies and interventions that address these disadvantages are necessary in order to improve educational outcomes in Côte d'Ivoire.

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