Contributions of Procedural Memory to Emergent Reading in Older Children

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Abstract

Research on emergent reading has focused almost exclusively on children who begin learning to read by age 5-6, despite the fact that many children around the world begin learning to read later in childhood. Little is known about how older children learn to read for the first time. Importantly, procedural learning supports children's ability to acquire new skills implicitly and apply those skills with automaticity. Procedural learning is therefore thought to support early reading and reading-related skills, such as phonological awareness. However, as children age they may become less reliant on procedural learning. Older children learn new language skills through largely explicit memorization as opposed to implicit procedural learning, and the same is potentially true for language adjacent skills such as reading. Older children may rely less on procedurally supported phonological awareness when reading for the first time and instead rely on explicit skills such as vocabulary. We examined the role of procedural learning in emergent reading across different ages (9-15 years), focusing on low-literacy communities in rural Côte d'Ivoire, where many children remain in emergent stages of reading even at the end of primary school and age for grade is highly variable. We find that the relation between phonological awareness and reading, and vocabulary and reading among older emergent readers depends on procedural learning.

Millions of children around the world, and particularly in low- and middle-income countries (LMICs), are at a high risk of illiteracy, yet little is known about learning to read in such low literacy contexts despite the unique challenges facing children's reading development. For example, in Côte d'Ivoire, children may enter school at an older age and attend school less regularly than their counterparts in high-income countries (HICs; UNESCO, 2016). As a result, many children in Côte d'Ivoire, even those who have attended primary school, do not learn to read (Heugh, 2011). The delay in reading education for children in LMICs and the poor literacy outcomes for these children raise important questions regarding how children learn to read for the first time at an older age.

Multiple cognitive and linguistic abilities predict reading (Jasińska & Petitto, 2018; Goswami, 2008; Hulme, Hatcher, Nation, Brown, Adams & Stuart, 2002; Rack, Hulme & Snowling, 1993; Pugh et al., 2001; Tannenbaum, Torgesen & Wagner, 2006; Stahl & Murray, 1994; Wagner & Torgesen, 1987). When learning to read an alphabetic script, a child learns to associate graphemes (e.g. letter, or letter combination, 'th') with phonemes ('θ'or 'ð'). This early decoding ability relies on a child's knowledge of language, and particularly on a child's metalinguistic knowledge about the segmental nature of speech (i.e. phonological awareness), that is, the awareness of and ability to manipulate sound units (Bradley & Bryant, 1983). A reader also learns to associate visual representations of letters and words with mental representations of phonological and semantic information; thus a child's vocabulary knowledge is also a key component of skilled decoding (Duff, Tomblin, & Catts 2015). Emergent readers rely heavily on phonological information when first learning to read, but as readers become more skilled, vocabulary knowledge becomes increasingly important to reading (Cain & Oakhill, 2014, Harm & Seidenberg, 2004).

The mapping between orthography, phonology, and semantics (Harm & Seidenberg, 2001; Pritchard et al., 2012) is the core of skilled reading and allows the reader to decode words with automaticity and quickly recognize exception words (i.e. words that don't sound like they look such as 'yacht'; Windfuhr & Snowling, 2001). Becoming a fluent reader involves learning patterns between orthography, phonology, and semantics over multiple exposures, and forming increasingly implicit associations among these levels of representation—a process that involves procedural learning (Morgan-Short et al., 2014; Mayor-Dubois, et al., 2016; Quam, Wang, Maddox, Golisch, & Lotto, 2018). Procedural learning is considered to be implicit learning that underlies automatic, subconscious knowledge (Squire 1992; Squire & Zola, 1998; Squire et al., 2004; Squire & Dede, 2015; note, implicit learning is not synonymous with procedural learning; evidence exists to suggest that aspects of declarative learning may be implicit, for a larger discussion, please see Ullman & Pullman, 2015) and supports the discovery of linguistic structure during learning (e.g. phonology, aspects of syntax). Procedural learning supports the ability to recognize the patterns of allowable sound combinations or morpheme constructions within a language across multiple exposures through the refinement of predictions (Bradley & Bryant, 1983; Hedenius et al., 2012; Ullman, 2004; Ullman et al., 1997; Ullman & Lovelett, 2018).

Learning the phonological patterns, or phonotactics (e.g., rules related to the permissible combinations of sounds and syllables in a language), across many words emerges through the implicit recognition of patterns (Avcu et al., 2019). This capacity to generate expectations for sequenced events (i.e. repeat exposures) in procedural learning is thought to account for the human language ability to predict what sounds should, and can, co-occur (Cohen, Poldrack, & Eichenbaum, 1997; Conway & Pisoni, 2008; Goschke, Friederici, Kotz, & Van Kampen, 2001; Warker, 2013). The predictions of common sound patterns in language facilitates the ability to map phonemes to their orthographic representation (Apel et al., 2006). Procedural learning also supports the ability to recognize patterns within the orthography itself by allowing the emergent reader to track the regularity with which a grapheme corresponds to the same phoneme (Brice et al., 2021; Brice et al., *in press*). Therefore, procedural learning plays a role in emergent reading acquisition through phonological awareness and grapheme-to-phoneme mapping.

A facet of procedural learning, statistical learning—the ability to generate predictions based on the frequency of co-occurring information, has been linked to reading (Simor et al., 2019; Erickson & Thiessen, 2015; Karuza et al., 2013; Ceballos et al., 2020; Arciuli & Simpson, 2012; Qi et al., 2019; Torkildsen et al., 2019; Zinszer et al, 2023; Zinszer et al, *in press*). For example, recent scholarship on statistical learning and reading shows that visual statistical learning relates to reading in children (age 9) and adults (Arciuli & Simpson, 2012). Furthermore, auditory statistical learning was also related to reading (specifically decoding nonwords), and the relationship between statistical learning and reading was mediated by phonological processing (Qi et al., 2018). Further evidence on statistical learning and reading comes from the finding that after several days of training with feedback for reading real words, children age 7 attending school in the United States were better able to learn the phoneme-to-grapheme relationship for vowels when they were exposed to these vowels in a greater variety of contexts (Apfelbaum et al., 2013). The results of Apfelbaum et al. (2013), indicate that the ability to acquire the phoneme-to-grapheme knowledge which underlies basic decoding skills is learned implicitly. Indeed, the ability to map graphemes to the phonemes they represent has been linked to greater activation of procedural learning-related brain areas such as the basal ganglia and inferior frontal gyrus (McNorgan et al., 2011). Together, these results suggest that procedural learning's role in reading chiefly involves phonological processing and grapheme-phoneme mapping.

However, as a child's reading skill increases, procedural learning may become less relevant to reading: emergent readers rely more heavily on phonological processing when first learning to read, but as emergent readers become more skilled, this reliance on orthography to phonology to semantics shifts towards a greater reliance on vocabulary knowledge and to more direct orthography-semantic mapping (Cain & Oakhill, 2014, Harm & Seidenberg, 2004). Within typically developing groups, younger children rely more heavily on the pattern learning supported by procedural learning while older children become more reliant and more skilled in declarative supported tasks (Mayor-Dubois, Zesiger, Van der Linden, & Roulet-Perez, 2016). Potentially, emergent reading may be increasingly supported by explicit, rather than implicit, learning as a learner ages. Those who learn to read for the first time later in life often struggle with decoding and even skilled ex-illiterate adults are less fluent readers than children who learned earlier in life (Greenberg et al., 2002). Potentially, this is due to the decreasing reliance on procedural learning and increasing reliance on explicit learning among adolescents and adults. Indeed, Arthur et al. (2021) found that adult performance in phonological awareness skills, such as blending and elison, were related to declarative, not procedural learning. The authors argue that this reliance on declarative memory was because older individuals can use vocabulary knowledge to access their phonotactic knowledge (Arthur et al., 2021). However, it is difficult to untangle the role that procedural learning might play in older emergent reading as little work has examined emergent reading beyond early childhood.

Here, we ask how procedural learning contributes to emergent reading across late childhood and adolescence. Specifically, we explore how procedural learning relates to letter, word, and nonword decoding and reading-adjacent language skills such as phonological awareness and vocabulary. The role of procedural learning in supporting emergent reading across development cannot be fully tested with learners in the contexts of the education systems in HICs because children enter school, and therefore begin learning to read, by age 5-7. The experiences of children learning to read for the first time beyond age 7 remain largely ignored leaving many open questions regarding how learning mechanisms support reading acquisition. To start addressing these questions, we examined reading development of children growing up in rural Côte d'Ivoire, where many children begin to learn to read at an older age, largely outside the age range that the scientific literature on emergent reading has examined.

The context of Côte d'Ivoire provides the opportunity to examine how older emergent readers learn to read. While the official age for school start in Côte d’Ivoire is between 6 to-9 years, many children in rural communities without official birth records may begin school as late as 12 years (Soungari, Francis, & Assoa, 2017; PASEC, 2014; Jasińska, Ball, & Guei, 2023). Children in rural Cote d’Ivoire are often approaching or within early adolescence when they receive their first experience with literacy, meaning that, not only might procedural learning be decreasing in importance for skill learning, but the interrupted and reduced experience with phoneme to grapheme mapping may not be sufficient to develop procedural representations to support emergent decoding.

This variability in reading exposure is a consequence of poverty, which can throttle a child's access to early, consistent, and high quality education. Additionally, frequent absences can lead to many children repeating grades. Variable age at starting school and frequent grade repetition accumulates during primary school, such that there is even great variability in ages for children attending the fifth grade in an Ivorian school. Multiple studies suggest that procedural learning reaches developmental maturity in childhood at some point around the beginning of adolescence (Finn et al., 2016; Mayor-Dubois et al., 2015). Variable age at starting school and frequent grade repetition lead to classrooms with both younger (before procedural learning is fully developed, ages 10 and younger) and older (after procedural learning should be fully matured, ages 11-15) children. As a result, students receive the same reading instruction, albeit at different stages of their development. We specifically focus on a low-literacy rural region of Côte d'Ivoire where less than half of children advance beyond a primary school education and many who complete primary school are still functionally illiterate (Heugh, 2011). Consequently, even children at the end of primary school (i.e. in the equivalent of the fifth grade) remain in an emergent stage of reading.

Little scholarship on reading development has focused on later childhood and adolescent emergent reading, despite the fact that many of the world's children learn to read later in life. Understanding the specific challenges of the older emergent reader is crucial as many of these children may never reach beyond the emergent reading stage. Specifically, procedural learning, as the system which supports foundational literacy skills such as phonological awareness, likely plays a key role in emergent reading and yet previous research suggests that older learners may rely less on procedural learning. Examining the role of procedural learning in emergent reading will, therefore, take the first steps towards a greater understanding of the needs of older emergent readers.

Methods

Participants

Fifty children in the equivalent of fifth grade (the second to last grade before graduating primary school) from six schools in the Adzope region of Côte d'Ivoire participated in this study. Two of these children were excluded due to experimenter error. Two children did not complete the reading measures. Two further children were excluded due to high error rate in the procedural learning task. The ages of the remaining children were 9-15, the average age 11.25 years, SD=1.37 (Boys: N=19, M=11.95, SD=1.51; Girls: N=25, M=10.72, SD=0.98). The age at which the children began school was calculated by subtracting the child's years in each grade (including grade repetitions) from the child's current age. Average age for a child to begin school was 5.8 years (SD=1.21) with a range from 4 to 9 years of age (Boys: M=6.26, SD=1.33; Girls: M=5.44, SD=1.00). Thirty-six of these children reported speaking a local language (i.e., Attié) and only sixteen reported speaking French (i.e., the language of education) at home.

Materials

Procedural learning task

The serial reaction time task (SRTT) has been widely used as a measure of procedural learning (Nissen & Bullemer, 1987; Desmottes, Meulemans, & Maillart, 2016; Willingham, Nissen, & Bullemer, 1989; Bogaerts, Szmalec, Hachmann, Page, & Duyck, 2015; Clark & Lum, 2017a; Clark & Lum, 2017b; Earle et al., 2020; Hunt & Aslin, 2001). A keyboard-based SRT task from Lum et al. (2012) was adapted for use on a tablet. To accommodate the use of a touchscreen, an arc array similar to Hunt and Aslin (2001) was used (see Figure 1). During the task, a target appears in one of several locations arcing around a central point. Targets were smiley faces appearing in one of four locations on the screen of a tablet, in an arc around a central sticker at the base of the tablet, see Figure 1. As the smiley face appeared in one of the four locations, the child was instructed to tap that face as quickly as possible with their fingertip. In between touching the smiley face, children were instructed to return their fingers to the sticker, or "home." During the first random block, training and scaffolding was provided by the researcher, according to the child's needs. Children were reminded to touch the faces as quickly as possible. For children who required more assistance, an experimenter would hold their hands and help them to touch the first few faces to illustrate the procedure.

The task (including the first few scaffolded trials) began with 40 trials (Block 1) of the smiley face appearing in a pseudo-random position where no location was immediately repeated. Next, 320 trials (Blocks 2-9) with the smiley face appeared in a ten item sequence of positions. The sequential trials were followed by another 80 trials (Blocks 10 and 11) of the smiley face appearing in a random location. Children who have learned the sequence in Blocks 2-9 will predict the next location of the smiley face based on that learned sequence, and decrease their reaction time over the sequenced blocks. When the learned sequence no longer applies (i.e., Block 10), children may continue to make predictions as if the smiley face was still following the sequence and thus increase their reaction time for the random blocks. The change in reaction time from the last block of the sequenced trials (Block 9) to the block of random trials (Block 10) provides a measurement of procedural learning.

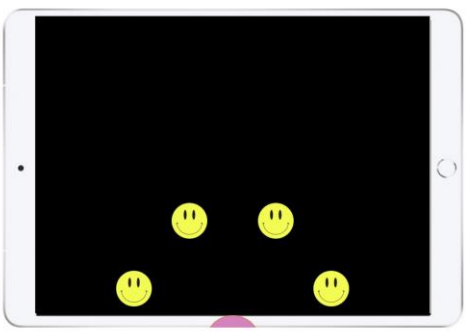
Language Measures

Phonological awareness. Phonological awareness tasks consisted of two components, 1) initial phoneme deletion (BELEC; Mousty, Leybaert, Alegria, Content, & Morais, 1994; Ball et al., 2022), where the experimenter read a word to a child and asked the child to repeat the word without the initial sound (e.g., 'cat' without the 'c' is pronounced 'at'), and 2) segmentation of French words (Yopp, 1995), where the experimenter read a word to a child and asked the child to repeat each sound of the word individually (e.g. ‘dog’ is ‘d’ ‘aw’ ‘g’).

Vocabulary measure consisted of synonym generation and antonym generation task. These tasks had been translated and abbreviated from the third edition of the Woodcock-Johnson test of cognitive abilities for use in Côte d’Ivoire (WJ-III-COG; Woodcock, McGrew, & Mather, 2001; Jasińska et al., 2022a; Ball et al., 2022). Each task consisted of 5 items. For the synonym task, children were given common French words (e.g., ‘mère,’ meaning mother) and asked to provide a synonym (e.g., ‘maman,’ meaning mom) of the word. For the antonym task, children were given common French words (e.g., "content," meaning happy) and asked to provide an antonym (e.g., "triste," meaning sad) of the word.

Reading measures were timed letter reading, word reading, and nonword reading tasks from the Early Grade Reading Assessment (EGRA; RTI International, 2009; Gove & Wetterberg, 2011) previously used in Côte d’Ivoire (Ball et al., 2022; Sobers et al. 2023; Zinszer et al., 2023). All of these tests were timed by experimenters with a cut-off beyond 60 seconds, as per EGRA testing protocol. For letter reading, children read 100 French graphemes and grapheme clusters (e.g., ‘e’, ‘m’, and ‘ch’) as quickly and as accurately as possible with experimenters marking incorrect responses. Word reading consisted of 50 French words (e.g., “monde”, “kilo”). Nonword reading consisted of 50 pseudowords which conformed to French phonotactics (e.g., “toche”, “donré”).

Figure 1: Example of the SRTT array



Socioeconomic checklist: Children were asked about items in their home (e.g., refrigerator, books, or motorcycle). The checklist from the EGRA (RTI International, 2012) and previously used by researchers in Côte d’Ivoire (e.g. Ball et al., 2022; Jasinska et al., 2022b). An SES score was the sum of these fifteen items. Using a checklist of household items rather than alternative measures of SES (e.g., maternal education or household income) is a preferable indicator of the relative status of a household in agricultural communities where income can vary with the seasons (Howe et al, 2012).

Protocol

IRB approval for the study was obtained at the University of Delaware and University of Toronto. Approval for the research program was also obtained from the Ivorian Ministry of Education. Consent was obtained from school directors, village chiefs, and the parent representative group (COGES); see Jasińska and Guei (2018) for detailed information about community consent procedures developed for the Ivorian context.

All experimenters were native speakers of Ivorian French. Testing took place on school property outside the child's classroom. After assenting to participate in the study, children completed all tasks for the current study (SRTT) and the larger reading intervention (demographic questionnaires, language and reading assessments) during their normal school hours. The entirety of testing lasted for roughly two hours per child. For tasks included in this study the testing time was roughly one hour. Children received a small gift (book and pencil) for their participation.

Statistical Analysis

For the SRTT task, reaction times were log transformed. Inaccurate trials were discarded (M=0.02% of trials, SD=0.04%, range= 0-16%). In the 9th and 10th block two subjects had over 15% errors. These two children were removed from further analysis. Trials with reaction times three standard deviations above or below the mean for each individual child were also discarded (M=2.66%, SD=0.93%, range=0.31-5.31%). The procedural learning score was determined by subtracting a child's mean reaction time in the 9th block (the final sequenced block) from their mean reaction time in the 10th block (return to random pattern after sequenced).

Statistical analysis was conducted using R Studio (RStudio Team, 2015; see supplementary materials for a complete description of the packages used). Variables were centered to avoid multicollinearity. With centering, variance inflation factor (VIF) for all variables was under 2.5 (Thompson et al., 2017).

Results

We first present descriptive results for each measure: age (and age at school start, and grade repetition), procedural learning, language (phonological awareness, vocabulary) and reading (letter, word, nonword reading) as well as the statistical relationships between these measures. We unpack the complex role of age in this sample by examining the factors related to being an older age learner (i.e., age at school start and grade repetition) and the statistical relationships between age and reading and reading-related skills (i.e., phonological awareness and vocabulary). These relationships were tested by Spearman correlation as these are better suited for non-normally distributed data (Zimmerman & Williams, 1997). Finally, we conduct a regression model testing the main effects and interactions between age, procedural learning, and language, and reading skills.

Age at School Start and Grade Repetition

Both age at which children started school and grade repetitions contributed to the variability in age in 5th graders. That is, a child who started school later would be older in 5th grade, and similarly a child who repeated grades would also be older in 5th grade. Unsurprisingly, age at time of testing and age at school start were highly correlated with one another, but age at school start and grade repetition were not correlated (p=.60), see Table 2. Some older children were older when they started school, the average age of starting school for children ages 11-15 was 6.27 compared to 4.79 for children aged 9-10.

Overall, the average number of grade repetitions was 0.48 (SD=0.59), with some children never having repeated a grade, while others repeated one to two times. Among the oldest children (ages 11-15) grade repetition was higher (M=0.60; SD=0.62), whereas among the youngest children (ages 9-10); grade repetition was lower (M=0.21; SD=0.43), this difference was significant ($t(35.82)=2.40$, p=.02). Additionally, SES was marginally correlated with grade repetitions ($\rho(46)=.25$, p=0.12) such that children of higher SES repeated grades more.

Procedural Learning

Children became faster as they learned the sequence. The first and last sequence blocks (2 and 9) were significantly different according to a paired sample t-test ($t(43)=5.51$, p<.001). Procedural learning was positively correlated with age; see Table 2). Figure 2B and 2C shows procedural learning of younger and older children.

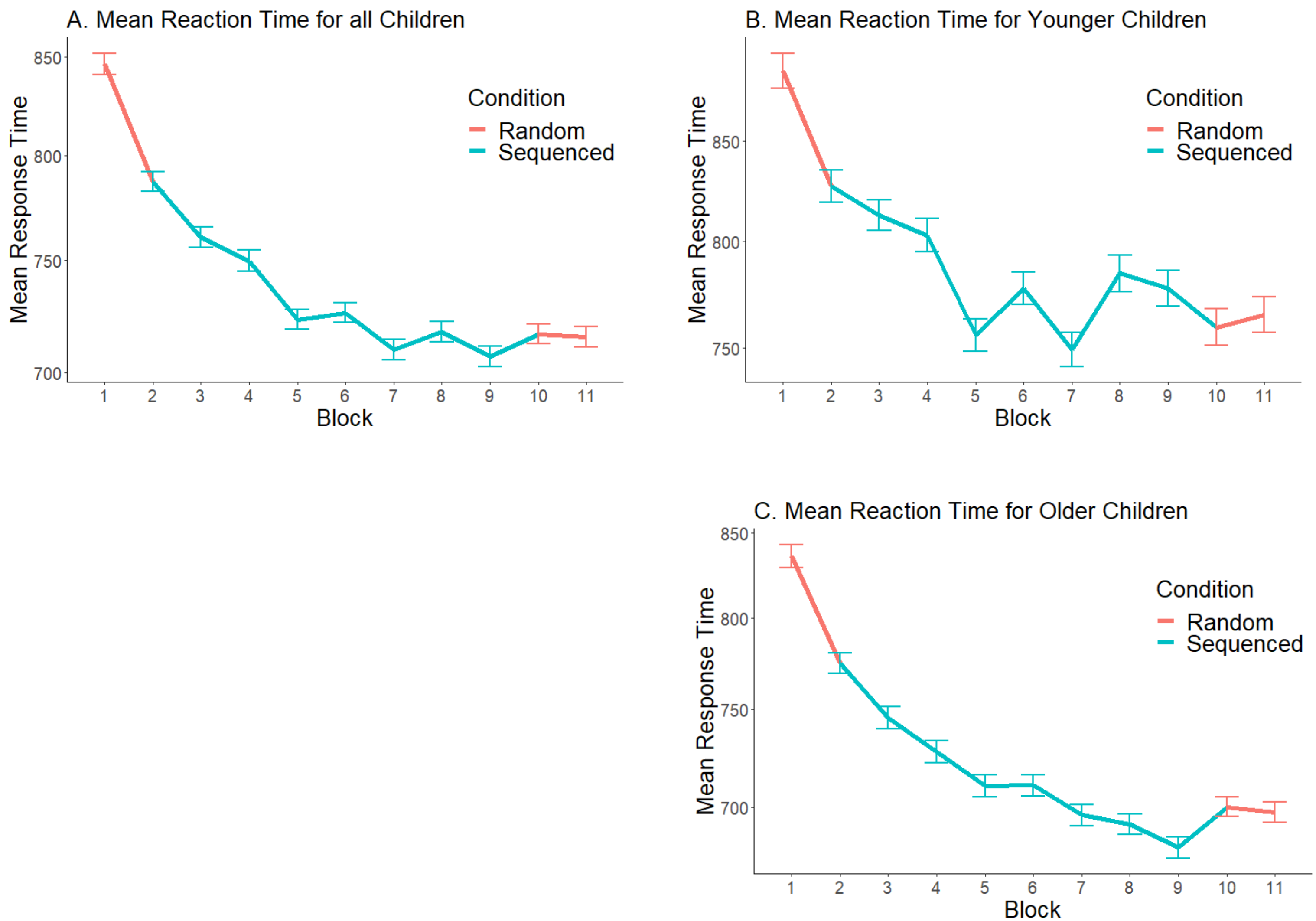
Table 1

Means and Standard Deviations for all measures.

Measure	M	SD
Age (9-15)	11.25	1.37
Age at School Start (4-9)	5.80	1.21
Grade Repetition (0-2)	0.48	0.59
SES (0-15)	4.95	2.40
Phonological Awareness (0-10)	2.82	2.97
Procedural Learning	0.01	0.10

Vocabulary (0-10)	3.23	2.07
Letter Reading (0-100)	29.32	21.70
Word Reading (0-50)	14.5	15.96
Nonword Reading (0-50)	9.86	12.013

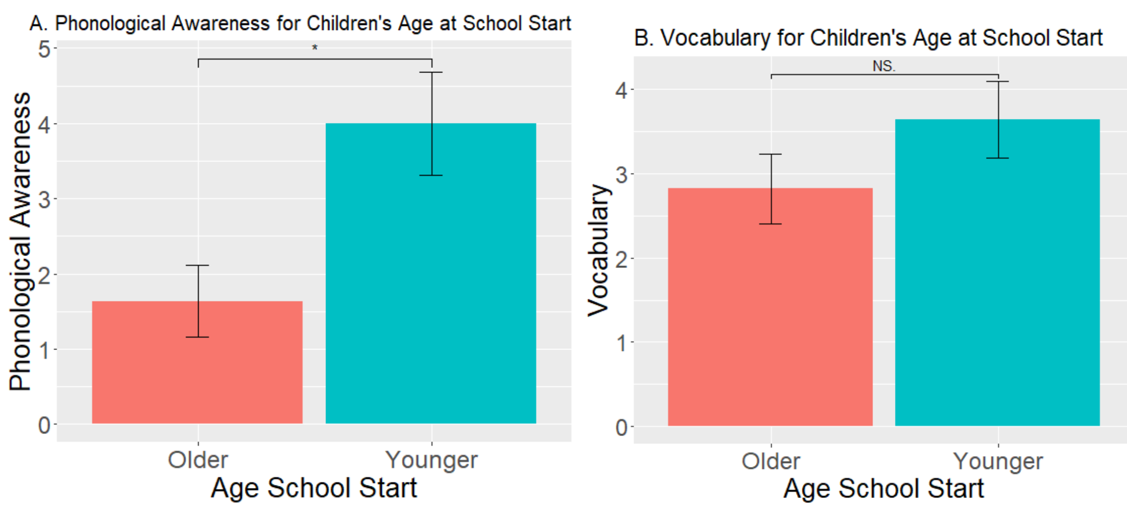
Figure 2. A. The mean reaction time for the SRTT at each block. B. The mean reaction time for the SRTT at each block for younger children. C. The mean reaction time for the SRTT at each block for older children. Error bars represent standard error.



Language

Phonological awareness was negatively correlated with age at the time of testing ($\rho(42)=-.36$, p=.02; see Table 2) and negatively correlated with age at school start ($\rho(42)=-39$, p=.009), but not correlated with grade repetition (p=.73). Vocabulary scores were not significantly correlated with age at the time of testing (p=.95), age at school start (p=.68), or grade repetition (p=.61; see Table 2). Further, children were divided by median split into groups for older age of school start (6-9; N=22) and younger age at school start (4-5; N=22). A t-test found that phonological awareness was significantly different between these groups (t(37.33)=-2.84 , p=.007; see figure 3A) but vocabulary was not significantly different (p=.19; see figure 3B).

Figure 3. A. Bar plot of phonological awareness scores for age at school start; older (6-9) vs. younger (4-5). B. Bar plot of vocabulary scores for age at school start; older (6-9) vs. younger (4-5). Error bars represent standard error.



Reading

Reading scores were low overall, see Table 1. Word and nonword reading scores were positively skewed (1.09, 1.22, respectively), reflecting the emergent reading levels of the sample, see Figure 4. Each reading test was correlated with both phonological awareness and vocabulary; see Table 2).

Figure 4. A. Histogram of Letter Reading scores. B. Histogram of Word Reading scores. C. Histogram of Nonword Reading scores .

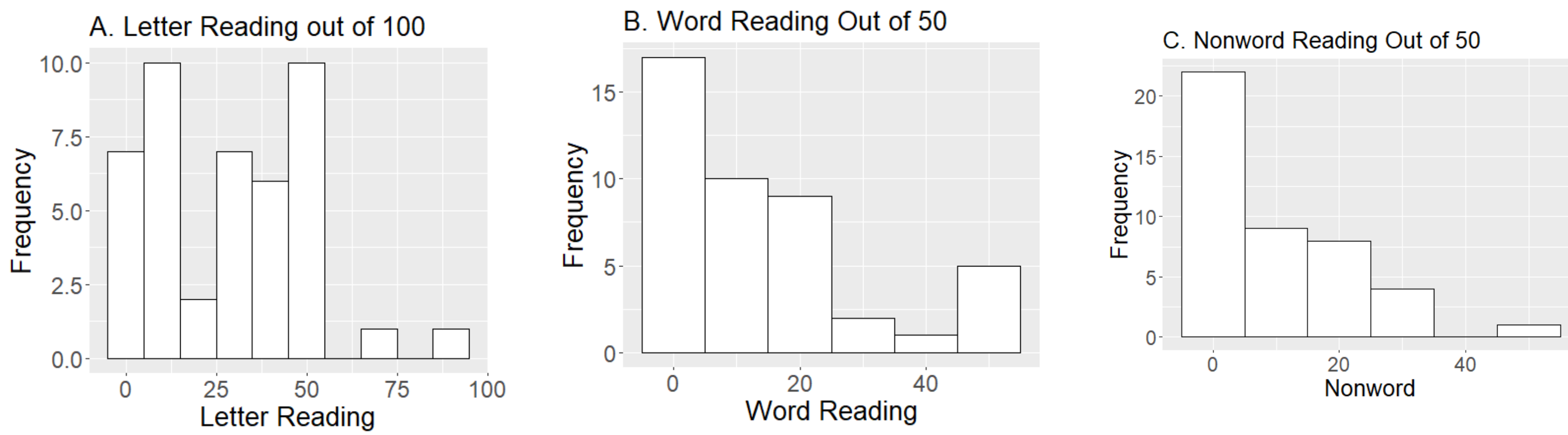


Figure 5. A. Scatterplot of reading scores for percent correct across three reading tests (Letters, Words, and nonwords) for age at the time of testing. B. Scatterplot of reading scores for percent correct across three reading tests for the age at school start.

Table 2

Spearman correlations without corrections.

	1	2	3	4	5	6	7	8	9
1. Age									
2. Year of School Start	.85***								
3. Grade Repetition	.41**	-0.06							
4. SES	-0.1	-0.14	0.25						
5. Phonological Awareness	-.30*	-.35*	-0.01	0.02					
6. Vocabulary	0.07	-0.03	-0.02	-0.2	.47**				
7. Procedural Learning	0.15	0.13	0.15	0.02	-0.2	-0.17			
8. Letter Reading	-0.15	-0.24	-0.07	-0.16	.45**	.52***	-.33*		
9. Word Reading	-0.19	-0.28	-0.08	-0.07	.60***	.45**	-.40**	.78***	
10. Nonword Reading	-0.12	-0.16	-0.09	0.02	.53***	.47***	-.31*	.70***	.85***

Note. * indicates $p < .05$. ** indicates $p < .01$.

Procedural Learning and Reading

A multiple linear regression estimated the effect of phonological awareness, vocabulary, procedural learning, socioeconomic status, age at time of testing, and grade repetition, and interactions between age and procedural learning, procedural learning and phonological awareness, and procedural learning and vocabulary on letter, word, and nonword reading.

There were significant main effects of phonological awareness and vocabulary for letter reading. Higher phonological awareness and vocabulary scores were associated with better letter reading scores. There were also significant interactions between procedural learning and phonological awareness and between procedural learning and vocabulary, see Table 3. For word reading, there was a main effect of phonological awareness. Higher phonological awareness scores were associated with better word reading scores. For nonword reading, there was a significant main effect of phonological awareness and marginal main effects of procedural learning and vocabulary. Higher phonological awareness and vocabulary scores were associated with better nonword reading scores. There was a marginal interaction between procedural learning and phonological awareness, see Table 3.

The interaction between phonological awareness and procedural learning was further evaluated using a simple slopes analysis (Aiken & West, 1991; Hughes, 2020; Figure 6A). This analysis examined the significant two-way interaction of two continuous variables by controlling for one of the variables and then measuring the effect of the other variable at different levels as determined by one standard deviation above and one standard deviation below the mean (Preacher, Curran, & Bauer, 2005; Aiken & West, 1991). For children with higher procedural learning scores (one standard deviation above the mean), phonological awareness significantly predicted letter reading ($b=0.89$, $t(34)=3.94$ $p<0.001$). For children with lower procedural learning scores (one standard deviation below the mean), phonological awareness did not predict letter reading ($b=-0.28$, $t(34)=-1.34$, $p=0.19$). The relation between phonological awareness and reading, therefore, was stronger for children with higher procedural learning scores.

The interaction between vocabulary and procedural learning was also further evaluated using a simple slopes analysis, see figure 6B. For children with higher procedural learning scores (one standard deviation above the mean), vocabulary did not significantly predict letter reading ($b=-0.03$ $t(34)=-0.13$, $p=.90$). For children with lower procedural learning scores (one standard deviation below the mean), vocabulary did significantly predict letter reading ($b=1.01$, $t(34)=3.43$, $p<.001$).

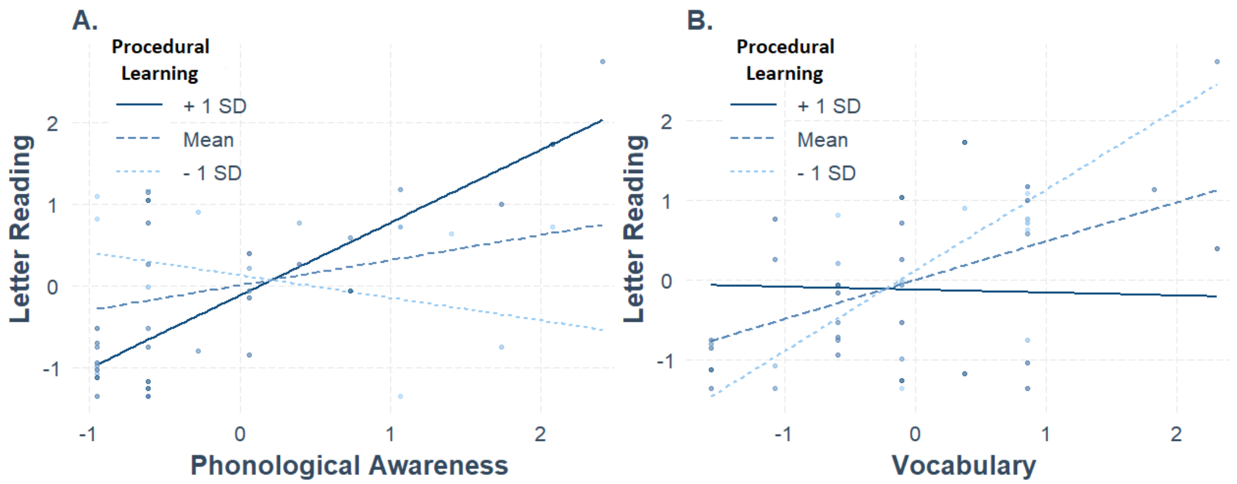
Table 3

Regression results predicting variations in letter reading, word reading, and nonword reading.

	Letter Reading	*Word Reading*	*Nonword Reading*
Predictor	β	β	β
Socioeconomic status	-0.01	0.05	0.13
Age at School Start	-0.05	0.10	0.16
Grade Repetition	-0.08	0.01	-0.13
Procedural Learning	-0.12	-0.19	-0.24 .
Phonological Awareness	0.31*	0.59***	0.58 ***
Vocabulary	0.49***	0.22	0.26 .
Age: Procedural Learning	0.08	0.03	0.08
Procedural learning: Phonological awareness	0.58**	0.19	0.31 .
Procedural learning: Vocabulary	-0.52*	-0.26	-0.32
Fit	R^2= 0.60 *** Adjusted R^2= 0.50	R^2= 0.56 *** Adjusted R^2= 0.44	R^2= 0.60 *** Adjusted R^2= 0.49

'***' indicates p <.001. '**' indicates p < .01. '*' indicates p < .05. '.' indicates p <.1

Figure 6. A. Simple slope analysis of letter reading's relation to phonological awareness at different levels of procedural learning. B. Simple slope analysis of letter reading's relation to vocabulary at different levels of procedural learning.



Discussion

This study examined the relation between procedural learning and emergent reading in late childhood and adolescence. We specifically focused on a low-literate, rural region of Côte d'Ivoire with a high rate of illiteracy, where the age at which a child enters school is highly variable. Consequently, children of very different ages learn in the same classroom. Despite reaching the fifth grade, the children in this study largely remained in an emergent stage of reading development (i.e., struggling to decode words; Heugh, 2011). We find that older children (ages 11-15) demonstrated better procedural learning than younger children (ages 9-10), suggesting age-related variation in procedural learning among children in the same classroom. Older children had poorer phonological awareness, a crucial skill for emergent reading. Overall, average performance on the letter, word, and nonword reading task was low, at 29.76, 30.91, and 20.17, percent correct, respectively. Many children struggled to decode a single word or nonword and remained in the emergent reading stage despite being in the fifth grade. The apparent disadvantage for reading among children who have been in school for at least five years highlights the importance of reading research in contexts where children learn to read late. Our findings indicate that the relation between phonological awareness and reading, and vocabulary and reading among children aged 9-15 depends on procedural learning.

Previous work, from HICs and LMICs alike, has outlined the importance of phonological awareness for emergent (typically younger) readers and the increasing importance of vocabulary for skilled (typically older) readers (Jasińska & Petitto, 2018; Tannenbaum, Torgesen & Wagner, 2006; Jasińska et al., 2019). However, while previous work almost exclusively examined emergent reading in younger children, here, we find that language skills similarly relate to emergent reading for older children and adolescents. Phonological awareness and vocabulary were both positively related to reading in our sample of 5th grade children and adolescents. Phonological awareness was related to letter, word, and nonword reading, suggesting that phonological awareness supports phoneme-to-grapheme mapping for emergent readers in low-literacy communities. Vocabulary was related to letter and nonword reading (marginally). This was a somewhat surprising result: word knowledge is not expected to be helpful for reading words that do not actually exist (Ricketts, Nation, & Bishop, 2007). However, it should be noted that nonword reading scores were extremely poor, and therefore, only the best readers scored well in the nonword reading task. These stronger readers also showed overall higher language skills (i.e., high scores in phonological awareness and vocabulary tasks), and importantly nonword reading was highly correlated with both phonological awareness and vocabulary. Therefore, the marginal relation between vocabulary and nonword reading may be a proxy for overall language skills and nonword reading.

Older children demonstrated poorer phonological awareness skills in comparison to younger children. The relation between phonological awareness and reading is reciprocal, not only does phonological awareness contribute to skilled reading, but skilled reading also supports phonological awareness. As a child learns to read, their metalinguistic knowledge of language increases, therefore better phonological awareness leads to better reading and better reading leads to better phonological awareness (Castles & Coltheart, 2004; Hogan, Catts, & Little, 2005; Wagner & Torgesen, 1987). Older children may then demonstrate poorer phonological awareness because they are poor readers.

Additionally, the disadvantaged phonological awareness for older children is likely a function of educational environment factors, such as starting school late or repeating grades (Whitehead et al., 2023; Wortsman et al., *under review*). Unsurprisingly, children who are older in the fifth grade were older when they started school. Late age at school start likely reflects factors associated with a child's home environment (i.e. child labor, parental illiteracy, poor home literacy environment), which contribute to poorer academic outcomes. The quality of the home reading environment and amount of reading exposure has been linked to reading outcomes (Dong et al., 2020; Georgiou et al., 2021; Leppänen et al., 2005; Harlaar et al., 2007). If the child's home reading environment is poor (i.e. no literate adults in their family, no access to books) then a later age at school also corresponds to later first exposure to reading.

Importantly, many children who participated in this study do not speak French as a first language and their exposure to French began when they started school, (Ayewa, 2018; Brou-Diallo, 2011) albeit this is five or more years ago for all children in the study. Later age at school entrance therefore means a later start in learning French, contributing to lower phonological awareness and reading scores. For children learning to read in a L2, earlier versus later age of acquisition is related to better reading. For example, children read words faster in an earlier-learned versus later-learned L2 (Dirix & Duyck, 2017).

Interestingly, a later age of school start was only negatively related with phonological awareness, but not vocabulary. The importance of early language exposure for phonological awareness fits well with existing language acquisition research on sensitive periods for the acquisition of phonology (Newport, 1993; Young-Scholten & Naeb, 2010; Hammick et al., 2018; Legult et al., 2018; Tarone, 2010; DeKeyser, 2008; Young-Scholten & Naeb, 2010; Grenfell & Harris, 2015). Specifically, as individuals age, the ability to learn phonology and syntax diminishes, while the ability to learn new vocabulary remains (Birdsong, 2018). Our findings of a significant relation between age and phonological awareness, but not between vocabulary and age, supports an earlier advantage for acquiring phonology.

Nonetheless, phonological processing appears to be important for readers of any age (Young-Scholten, 2015). We found that the relation between phonological awareness and reading was stronger for children with better procedural learning, suggesting that procedural learning supports the skills vital for emergent reading. In contrast, the relation between vocabulary and reading was weaker for children with better procedural learning. That is, procedural learning had an opposite moderating effect on the relation between vocabulary and reading, compared to phonological awareness and reading. This suggests that vocabulary skills may be more relevant to emergent reading for children with poor procedural learning, and for whom explicit word knowledge rather than implicit decoding offers an alternate route to reading. The relation between vocabulary and reading corroborates recent work from Côte d'Ivoire which found that 6th grade children between 10-18 years of age relied more on their semantic knowledge of French for reading instead of their knowledge of grapheme-to-phoneme mappings (Brice et al., *in press*).

This result suggests new directions for exploring the potential competition between declarative and procedural learning, outlined in the Declarative Procedural Model (DPM; Ullman, 2015). The DPM suggests that procedural and declarative memory support different aspects of language learning and reading. However, as declarative memory matures (at a more protracted rate compared to procedural, stretching into adulthood) it can start to compete with procedural learning (Ullman 2001; Ullman 2004; Ullman & Pullman, 2015; Ullman, & Lovelett, 2018). It is this competition which gives rise to the less efficient and less fluent language learning among adolescents and adults, particularly the structural aspects of language such as phonological processing and, potentially, phoneme-to-grapheme mapping. Our findings suggest that learning to read at an older age may be less efficient if learning is explicit (supported by declarative learning) and suggests important avenues for future research to test the contributions of both procedural and declarative learning to emergent reading across a broad age range.

Crucially, our findings indicate the continued importance of phonological awareness for older emergent readers, and that the link between phonological awareness and reading depends on procedural learning. Understanding the specific role of procedural learning in reading development is then very relevant for appropriately addressing the issues facing older children learning to read for the first time.

Limitations and Future Directions

In rural Côte d'Ivoire, the age at which a child is first introduced to reading as well as the consistency of their reading education is highly variable. Additionally, there are more than 60 different languages spoken in Côte d'Ivoire, and the majority of Ivoirans either speak French as a second or speak no French at all (Madaio, 2019). Many children in Côte d'Ivoire, therefore, are learning to read for the first time in their second language, a language that they may not be exposed to anywhere else but in school. Reading in Côte d'Ivoire, is then not just emergent reading at an older age, but reading at an older age in a second language. Further work should explore reading in the second language in this context.

As mentioned above in the discussion, the findings of the present study may provide new insight for the Declarative Procedural Model, which suggests that maturational timeline of procedural learning (which matures early in childhood) and declarative learning (which matures at a more protracted rate into adulthood) is the key to explain the apparent shift from procedural (implicit) learning to more declarative (explicit) learning. Specifically, declarative learning becomes more important for skill development as it matures and competes with procedural learning when the systems overlap in the skills they might support. Indeed, previous work points to the changing importance of these learning systems for reading (Earle et al., 2020). Further research should examine how more developed declarative learning may impact the learning strategies of older emergent readers, testing both declarative and procedural learning's unique contributions to reading including contributions to vocabulary and phonological awareness.

Conclusion

Previous reading research has almost exclusively focused on the experiences of children learning to read for the first time around the ages of 5-7. Millions of children worldwide enter school after the age of 7. In this study, we examined how learning development, particularly procedural learning, impacts reading development in older emergent readers. We found that procedural learning does impact older emergent reading through its support of phonological awareness. Understanding the importance of procedural learning in this context provides valuable information regarding reading development beyond early childhood. This understanding is especially important since phonological awareness may be vulnerable to age and environmental factors (i.e. school entrance and school attendance) that can be exacerbated by poverty. Additionally, this study contributes to greater understanding of the relation between procedural learning and reading and reading-related language skills. Expanding the reach of reading research can provide valuable insight which can inform interventions that can help children everywhere attain reading.

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Supplementary Material

Statistical analysis was conducted using R Studio (RStudio Team, 2015). Data cleaning and transformation were conducted using the R packages ‘plyr’ (Wickham, 2011) and ‘tidyverse’ (Wickham, 2019). Correlations for testing the relationship between age or grade repetition to other variables such as language, literacy, or procedural learning were conducted using the R package ‘psych’ (Revelle, 2019). Regressions to examine the effects of age, phonological awareness, vocabulary, and procedural learning on reading were also conducted using the R package ‘stats’ (R Core Team, 2012) and ‘lm.beta’ (Behrendt, 2023). Variables were centered to avoid multicollinearity using the function ‘scale’ (R Core Team, 2012). Simple slope analysis to examine interactions between continuous variables and the visualization of this interaction was generated using the R package ‘interactions’ (Long, 2019). Other visualizations were generated using the ‘ggplot2’ (Wickham, 2016) and ‘ggpubr’ (Kassambara, 2020) packages.