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An exploratory analysis of divergent patterns in reading progression during a tablet-based literacy program

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We conducted exploratory research on divergent patterns in reading progression among early grade learners in a low-resourced community to identify key determinants of high versus low reading progress. The sample comprised 30 learners who were purposively selected from participants in a 13-month tablet-based literacy program at a peri-urban Malawi primary school to represent high and low progressing readers. We employed stepwise logistic regression to test the independent contributions of (1) a composite measure of home literacy and language environment, and (2) a direct assessment of working memory skills, to a binary measure of reading progress status, controlling for children's age. Our results showed that children's working memory skills uniquely predicted high versus low progress in reading over and above other known predictors of early literacy development. These findings point to the importance of working memory skills as a key determinant of reading progress in the context of a tablet-based literacy program in a developing country. As education technology programs proliferate in low-income countries, results from our study offer an evidence-based strategy for identifying and supporting learners who are at risk for non-progress in reading during a tablet-based literacy intervention.

KEYWORDS

reading progress, education technology, working memory, home language and literacy environment, international development

Introduction

EdTech interventions have been widely established as one of the most effective education interventions in developing contexts (McEwan, 2015; Damon et al., 2016; Conn, 2017). A review of rigorous impact studies in sub-Saharan Africa showed that pedagogical methods, including blended or technology-assisted learning, were more effective than school management, school supplies, class size or composition, and health treatments or school meals (Conn, 2017). An additional review of randomized experiments in developing countries showed that the use of computers or instructional technology was more effective than teacher training, class organization, performance incentives, instructional materials, and deworming (McEwan, 2015). Technology-enabled instruction improved learning outcomes in developing countries in 7 out of 8 high-quality studies reviewed by Glewwe and Muralidharan (2016). Additionally, in a comprehensive review of education policies, programs, and interventions in developing countries, Damon et al. (2016) categorized EdTech interventions among the "interventions that often work," noting that the program impacts appear to depend on careful integration of effective pedagogical techniques with technology.

Research conducted in Africa since 2015 has shown that high-quality, tablet-based instruction can produce meaningful impacts on literacy development in both in-school and out-of-school settings (Pitchford, 2015; Pitchford et al., 2017; King et al., 2019; Levesque et al., 2020, 2022).

Early research in Malawi demonstrated an impact in overall literacy of 0.42 standard deviations after 14 weeks (Pitchford et al., 2017). A 15-month RCT conducted for the Global Learning XPrize with out-of-school children in Tanzania produced effect sizes of 0.46–0.59 in early literacy skills (King et al., 2019). Further, two recent longer-term randomized controlled trials (RCTs) with Malawian Standard 2 learners in government primary schools in 2018–2019 (8 months) and in 2019–2021 (13 disrupted months) produced effect sizes of 0.34 and 0.37 in overall literacy, respectively (Levesque et al., 2020, 2022). However, while these interventions produced average positive literacy effects, further analysis revealed that a substantial portion of children who used the tablet-based curriculum remained non-readers at the end of the intervention periods: 77% after 8 months and 42% after 13 months. Being a "non-reader" means not being able to read a single word of connected text (words presented in sentences and paragraphs), as measured by the Early Grade Reading Assessment (EGRA; RTI International, 2015). Yet, little research has explored why some children benefit from exposure to a tablet-based literacy curriculum whereas others do not, particularly in a developing context.

Theoretical framework and literature review

Home literacy and language environment

The term home language and literacy environments (HLLE) refers to language attributes and literacy-linked processes in children's homes that have been shown to relate to literacy development (Nag et al., 2019). The degree to which children have opportunities to engage with texts, both independently and with other family members, as well as observe literacy practices within the home has been widely established as a predictor of early literacy (Daneman and Carpenter, 1980; Rojas-Barahona et al., 2015; Follmer, 2018). Home literacy also includes forms of spoken language and, thus, children's exposure to language in the home environment also represents an important determinant of early literacy development (Dickinson et al., 2012; Golinkoff et al., 2019). The degree to which parents read and talk to their children fosters the competencies that support them in acquiring listening and reading comprehension skills (Dickinson et al., 2012) as well as attention-focusing skills (Mendelsohn et al., 2018).

While most studies have investigated how the quality of HLLE relates to children's learning in developed countries, there is a growing body of research focused on the relevance of HLLE for children's literacy development in developing contexts as well (Nag et al., 2019; Friedlander, 2020; Kim et al., 2020). Recent meta-analyses (Nag et al., 2019; Kim et al., 2020) have found consistent associations between home language and literacy activities and children's literacy acquisition. Home literacy and language activities include the number of books in the home, tutoring, and adult literacy practices (e.g., modeling reading practices, daily use of literacy) (Nag et al., 2019). A 2020 meta-analysis conducted by Kim et al., on the impact of literacy interventions on reading skills in low-and middle-income countries found small, significant associations between literacy interventions that included community involvement (e.g., specific activities to support HLLE), children's emergent literacy skills ($d = 0.25$) and reading fluency ($d = 0.18$). In addition, Friedlander (2020) conducted a deeper investigation into how underlying factors of children's home literacy environment related to early grade reading achievement in Rwanda. This study employed factor analysis to identify five distinct factors of the home literacy environment: family literacy and learning at home, parental competency in literacy, reading materials, child interest in literacy and religious-related reading activities. Multivariate regression analysis using the five factors as independent variables to predict reading outcomes (i.e., letter identification, decoding, reading fluency and comprehension) showed that only family learning, parent competency and child interest emerged as significant predictors of reading outcomes. The current study extends prior work by measuring the unique contribution of children's HLLE environment to high versus low progress in reading in a developing country.

Working memory skills

In recent years, children's working memory skills have been widely established as an important predictor of children's reading achievement. The term working memory refers to a child's ability to hold, update, and manipulate verbal or nonverbal information in the mind over short periods of time (Diamond, 2013). Working memory skills are hypothesized to support early literacy development and comprehension skills by allowing children to simultaneously process verbal or visual information, activate relevant background knowledge or concepts, as well as integrate information across these processes (Daneman and Carpenter, 1980).

A wide array of research has established empirical links between children's working memory and literacy development. Several recent meta-analyses examining associations between children's executive functioning (EF) skills and reading achievement have established a positive and consistent association between working memory skills and reading achievement (Jacob and Parkinson, 2015; Follmer, 2018; Peng et al., 2018). For example, a study by Demagistri et al. (2014) examined whether adolescents who showed high versus low reading comprehension demonstrated corresponding differences on two measures of EF, working memory and inhibition, controlling for age. Specifically, this study found that high performing readers scored higher on a direct assessment of working memory compared with low performing readers, who showed correspondingly lower vocabulary and working memory processing skills. Further, in a study that examined differences in performance in number and word updating tasks among elementary school-aged children with and without reading deficits, children with poor reading comprehension performed worse on measures of the word updating task, but not the number updating task, compared to children without deficits (Pelegrina et al., 2015). The authors hypothesized that lower performance on the word updating task for learners who showed poor reading comprehension suggested that these difficulties were domain-specific. Together, these findings highlight how working memory skills support children in retaining, updating and applying phonological information in order to gain the foundational decoding and language comprehension skills that underlie reading comprehension.

While most prior work has examined the contribution of working memory to children's reading achievement in high-income countries, a growing body of evidence has established the relevance of these skills for early literacy development in developing contexts (Obradović and Willoughby, 2019; Willoughby et al., 2019). In a 2014 research study by Engel de Abreu et al. (2014), working memory emerged as the strongest predictor of reading among 6–8 year-old children in Brazil. Other studies focused on early childhood and employed direct assessments to

examine working memory skills as part of a composite that broadly captured children's EF skills, which included inhibitory control and/or cognitive flexibility in addition to working memory, as a predictor of reading achievement. These studies established positive associations between children's EF skills and early literacy skills among a large sample of learners in Kenya (Willoughby et al., 2019) and Ghana (Wolf and McCoy, 2019). Recent work conducted on a sample of primary school-aged learners (6–14 years old) in rural Ivory Coast found that children's EF skills, as indexed by working memory and inhibitory control, were the largest predictor of literacy over measures of children's learning environment and physical development (Jasińska et al., 2022). Nonetheless, no study to date has examined working memory as a unique predictor of high versus low progress in reading during a tablet-based literacy program, over and above other factors known to support literacy development.

Current study

In the current study, we examine divergent patterns in reading progression among children who participated in a recent 13-month tablet-based literacy program at a peri-urban Malawi primary school to identify factors that may help explain why some learners made gains in early reading skills whereas other similar learners did not. We focus on factors known to influence early literacy development according to the Simple View of Reading (Gough and Tunmer, 1986; Nation, 2019), which puts forth that reading comprehension is primarily dependent on two foundational skills: children's language comprehension and decoding. Specifically, we examine how HLLE (Sénéchal et al., 2017; Nag et al., 2019; Friedlander, 2020) and children's working memory skills predict high versus low progress in reading (Daneman and Carpenter, 1980; Engel de Abreu et al., 2014; Follmer, 2018). Findings from this exploratory study will be used to identify factors associated with non-progress in reading, thus setting the foundation for future work that will involve: (1) guiding the development and testing of strategies for improving the software to benefit all learners; and (2) informing future research to investigate a wider array of factors that can be used to develop profiles of children who are not making progress in literacy.

Our study investigates how the quality of HLLE and working memory skills independently relate to children's high versus low progress in reading. We employ stepwise logistical regression to examine the unique contribution of each factor to a binary variable that captured the highest progressing learners at midline (including those who attained emergent or fluent reader status by endline) and the lowest progressing learners at midline (including those who remained non-readers or low readers at endline). Endline reader status is based on the Malawi government benchmarks for reading (USAID, 2015a).

Since prior research has shown that multiple aspects of children's HLLE relate to literacy development (Nag et al., 2019; Friedlander, 2020), we created an HLLE composite variable that examined the overall degree to which children were exposed to a range of literacy and language supports in their home environment. We hypothesized that households in which children had more exposure to literate adults, literacy materials, a Bible, a radio and help with homework would benefit from higher exposure to literacy and language practices (Dickinson et al., 2012; Nag et al., 2019; Friedlander, 2020) and be more likely to show high compared with low progress in reading.

Previous work establishing working memory as a robust predictor of reading achievement (Follmer, 2018; Peng et al., 2018) suggests that children who show better working memory skills would be more likely to retain and apply information while working on a tablet-based curriculum. We hypothesized that children who showed strong working memory skills would benefit more from the literacy program and demonstrate higher progress in reading. Based on prior research showing that working memory skills predicted literacy over and above the home literacy environment (Jasińska et al., 2022), we also expected working memory to emerge as the strongest predictor of children's reading progress status. Thus, our study seeks to contribute new insight into the relative contributions of HLLE and working memory as important determinants of reading progress, specifically in the context of a tablet-based literacy program in a developing country.

Materials and methods

Contextual background

Participants in the study represent a small subset of children who participated in our 13-month RCT in Malawi. This long-term study launched in October 2019 with approximately 600 Standard 2 children in two government primary schools located in an urban and a peri-urban area. Conditions in the urban and peri-urban communities and schools are challenging. Families tend to be very low income and face food insecurity and other poverty-related challenges. At the school, class sizes are very large and can include up to 100 children. In addition, absenteeism is a persistent problem due to a variety of factors, including household demands such as caring for younger siblings and hazardous road conditions between children's homes and school during heavy rains.

The study was originally intended to span two school years (16 months) through June 2021. However, due to school closures and necessary adjustments to the normal school calendar as a result of the COVID pandemic, the study spanned two disrupted school years. During School Year 1, the program ran from October 2019–March 2020 (5 months of intervention) and from October 2020–December 2020 (2 months of intervention). During School Year 2, the program ran from March 2021–October 2021 (6 months of intervention). Ultimately, children participated in the intervention for 13 months, after accounting for school holidays and exam periods.

Current study design

We employed a mixed-method, multi-informant approach to collecting data on key factors that relate to early literacy development. Through interviews with children and parents, we collected data on children's demographics, home environment, school engagement, and health functioning. We also directly assessed children's working memory skills.

Participants

Since the current study was designed to be an exploratory investigation into the issue of non-progress in reading, we selected a small and purposive sample of 30 learners representing high and low progressing learners in reading who attended the peri-urban government primary school. To purposively select our sample, we first identified learners who had attended at least 50% of the days the tablet

program was offered and who showed very low baseline literacy achievement (i.e., scored 5 points or fewer on the baseline EGRA administered in October 2019). Among these learners, we examined the distribution of midline learning gains based on children's total scores on the overall EGRA to purposefully select 15 learners who showed the most progress and 15 learners who showed the least progress in reading from baseline to the midline assessment in October 2020.

The study was conducted during the final term of School Year 2 (September–November 2021). The final study sample was majority female (60%) and 9.3 years old on average at the time of data collection in September–November 2021. These sample characteristics were consistent across high and low progressing learners. Over the course of the long-term study period, the majority of learners (80%) were promoted from Grade 2 in School Year 1 to Grade 3 in School Year 2. However, there were differences in promotion rates between high and low progressing learners: 100% of high progressing learners and 60% of low progressing learners were promoted to Grade 3 in the 2021 school year. The remaining 40% of low progressing learners were still in Grade 2 at time of data collection.

Onecourse tablet-based literacy program

The intervention program using onebillion's *onecourse* software is called "Unlocking Talent through Technology" (Unlocking Talent) and typically focuses on Standard 2 children. The curriculum follows accepted literacy pedagogy and is loosely aligned to the Malawi national education standards (Ministry of Education Science and Technology, 2015). Children progress through the tablet curriculum at their own pace. Tablet sessions are delivered in a free-standing learning center on the school campus, enabling strong oversight of attendance and mitigating against research contamination. Children in the literacy treatment group step out of different standard classes on different days to use the tablets for 40 minutes per school day. This rotation schedule mitigates against instructional substitution effects, with treatment group children on average obtaining an additional 40 percent of time in the tablet subject over standard classroom instruction of that subject.

Measures

Reading progress status

As part of the larger RCT, we assessed children at baseline (October 2019), midline (October 2020), and endline (November 2021) using EGRA. Additional data for the reading progress study were collected in September–November 2021. Thus, the endline EGRA occurred after data collection for the reading progress study. High and low progressors in reading were identified using baseline and midline EGRA data and then their status was confirmed during analysis using the endline EGRA data.

Among children who met the study criteria of showing very low literacy achievement at baseline (<=5 total points out of a possible maximum of 371) on the EGRA and who attended the program at least 50% of the days that the program was offered, we examined the distribution of learning gains based on children's total score on the overall EGRA to identify children who showed the least progress ($M = 0.87$, $SD = 1.30$) and the greatest progress ($M = 51.87$, $SD = 30.74$) from baseline to midline. At the end of the intervention, we confirmed that these learners showed endline achievement that was consistent with their midline reading progress status. In general, we found that learners who had showed the highest progress at midline continued to demonstrate high progress in reading, whereas learners who showed the least progress at midline continued to show low reading progress. There were only two exceptions: one low progressing learner demonstrated unexpectedly high gains from midline to endline and one high progressing learner demonstrated relatively flat achievement from midline to endline. Thus, we redesignated these two learners to more accurately reflect their baseline to endline achievement patterns. At the end of the intervention, learners' total score gains on the overall EGRA from baseline to endline showed a clear divergence in reading progression across high progressing ($M = 156.93$, $SD = 34.43$) compared with low progressing ($M = 38.67$, $SD = 25.85$) learners. Further, learners' progress toward Malawi government benchmarks for reading progress status[1] showed that high progressing learners progressed from non-readers at baseline to attain either emergent (53%) or fluent (47%) reader status at endline, whereas low progressing learners either remained non-readers (47%) or attained low reader status only (53%) from baseline to endline.

Home literacy and language environment

The home literacy and language environment (HLLE) composite is designed to measure learners' experience in their typical home environment in the following areas: literacy, spoken language, and engagement with text experience. HLLE includes five questions pertaining to the presence of the following literacy and language supports in the household: (1) reading materials, (2) Bible, (3) family members who can read, (4) radio, and (5) homework help. For example, to gather insight into factors facilitating reading, both learners and parents were asked, "Are there any books, newspapers, or other things to read at home, other than your/your child's school textbooks?" For insight into education background, parents and learners were asked, "Does anyone help you/your child with homework or class work outside of school?" Items are given a 1 for "yes" and a 0 for "no." The five items met internal consistency standards for reliability ($\alpha = 0.75$). Further, we ran a principal components analysis to confirm the uni-dimensionality of the items. Results indicated that all five items loaded positively onto the same factor, with factor loadings of 0.31 or higher. To produce the HLLE composite, we ran a one-parameter (1PL) logistic item response theory (IRT) model to derive a predicted latent trait variable that captured the overall quality of HLLE.

Working memory assessment

We administered a simple picture span task to directly assess children' working memory skills using procedures adapted from Daneman and Carpenter (1980). Since two of the co-authors of the current study are from Malawi, we were able to ensure that all pictures

1 The Malawi Ministry of Education, Science and Technology has proposed a Standard 2 benchmark for oral reading fluency of 40 correct-words-per-minute (cwpm) (USAID, 2015a). The Zambian government set additional interim Standard 2 benchmarks for the Chichewa ("Nyanja") language (USAID, 2015b). These benchmarks included: non-reader (0 cwpm of reading connected text); low reader (1 to 19 cwpm); emergent reader (20 to 30 cwpm); fluent reader (40+ cwpm).

selected for the assessment included images that Malawian school-aged children could easily recognize from their daily lives. During the assessment, enumerators administered a practice trial to ensure that children understood the task before proceeding with experimental sets. Children were also warned to expect the number of pictures to increase during the course of the test.

The task comprised seven experimental trials during which stimuli were presented at a rate of one per second, beginning with a set of two. Within each trial, stimuli were grouped into three sets each of 2–7 objects. For each set, children were asked to recall all the stimuli in the exact order of presentation. Enumerators administered sets of increasing length up to 7 until a level was reached at which the child failed all three sets. We calculated a total span score that summed the total of all pictures correctly recalled, regardless of whether the trial led to perfect recall, for the 28 learners who had valid data. Of the two learners who were missing working memory data, one learner failed the practice trial and one learner was incorrectly identified as failing the third trial and prevented from proceeding in the assessment. After data collection, we also discovered that enumerators appeared to have accidently skipped one trial for four learners. However, since these four learners proceeded normally until they failed a trial; we concluded that the working memory data for these learners were still valid.

To calculate reliability, we used a split part reliability approach (La Pointe and Engle, 1990) to randomly assign 1 of the 3 trials in each set (from 2 to 7 objects) to a new total score composite, exhaustively assigning the three trials to three new composites. We calculated Cronbach's alpha separately for each split composite. Results indicated that Cronbach's alpha for all composites was 0.73 or higher, thus indicating that reliability for the picture span total score met the minimum threshold for internal consistency (i.e., $\alpha >= 0.60$).

Covariates

To gather children's ages, all learners were given a questionnaire to collect basic demographic information. Learners were asked "How old are you?" Child age was recorded by the number of years given.

Missing data

Since we were missing working memory assessment data for two learners, we excluded these learners from the bivariate correlation and logistic regression analyses. Thus, our final analytic sample comprised 28 learners who had complete data for all study variables: working memory, HLLE composite and age. Table 1 presents descriptive statistics for the final analytic sample, both overall and by reading progress status.

TABLE 1 Descriptive statistics for analytic sample.

Variable	Full analytic sample	High progressing learners	Low progressing learners
Child demographics			
Child gender (% Female)	57%	60%	54%
Child age (mean, SD, *in years*)	9.43 (1.23)	9.6 (1.12)	9.23 (1.36)
HLLE characteristics (% yes)			
Whether household has reading materials	68%	73%	62%
Whether any household members can read	92%	100%	85%
Whether household has a Bible	64%	73%	54%
Whether household has a radio	39%	33%	46%
Whether child receives homework help in household	64%	53%	77%
Working memory (mean, SD)			
Total span score	34.2 (18.74)	42.9 (20.09)	24.2 (10.87)
Achievement on EGRA (mean, SD)			
Baseline	2.0 (1.36)	2.3 (1.28)	1.7(1.45)
Midline	30.2 (37.27)	53.2 (32.11)	3.7 (4.04)
Endline	102.2 (69.29)	129.2 (34.60)	23.4 (25.52)
N	28	15	13

Analytic sample was limited to learners who had complete data for all study variables: working memory, HLLE composite, and age.

Results

Bivariate correlations

We ran bivariate correlations to examine whether key study variables were associated with each other in the expected direction. Children who scored higher on the working memory picture span task were significantly more likely to be high compared with low progressing readers, whereas the HLLE composite did not relate to reading progress status. However, for older children, parents were less likely to report having reading material or a Bible at home. The overall quality of children's HLLE was also marginally and negatively correlated with age. As expected, parents who reported having reading materials in the house also reported having a Bible and literate household members. Households in which parents reported that their child received homework help were also more likely to have a Bible and radio. Children's reading progress status was not significantly associated with any component of HLLE (i.e., household reading materials, literacy status, Bible, radio, or homework help). Bivariate correlations among all study variables are presented in Table 2.

Logistic regression results

Logistic regression analysis was conducted to identify factors that predict children's high versus low progress in reading. We examined predictors of children's reading progress status in a stepwise fashion. For each model, we employed penalized maximum likelihood estimation to reduce small-sample bias of the usual maximum likelihood of logit coefficients Rainey and McCaskey (2021). We controlled for children's age in step 1. We examined the association between the quality of children's HLLE, over and above age, in step 2. We tested the significance of children's working memory over and above HLLE and age in step 3. Children's total score on the direct

TABLE 2 Bivariate correlations.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1. Child age	–							
2. Whether household has reading materials	−0.33+	–						
3. Whether any household members can read	−0.25	0.40*	–					
4. Whether household has a Bible	−0.41*	0.92***	0.37+	–				
5. Whether household has a radio	−0.04	0.24	0.22	0.29	–			
6. Whether child receives homework help in household	−0.23	0.44*	0.08	0.38*	0.14	–		
7. HLLE composite (latent predicted score)	−0.37+	0.85***	0.50**	0.84***	0.61***	0.63***	–	
8. Working memory total span score	0.04	0.19	0.34+	0.28	−0.01	0.04	0.18	–
9. Reading progress status (high vs. low)	0.15	0.13	0.30	0.20	−0.13	−0.25	0.00	0.50**

+$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

TABLE 3 Stepwise logistic regression for factors that predict reading progress status.

	(1)	(2)	(3)
	Model 1	Model 2	Model 3
Child age	1.262	1.302	1.234
	(0.384)	(0.424)	(0.457)
HLLE composite (latent predicted score)		1.161	0.870
		(0.546)	(0.458)
Working memory total span score			3.367*
			(1.930)
Constant	0.127	0.095	0.181
	(0.368)	(0.293)	(0.630)
Observations	28	28	28

Exponentiated coefficients. Standard errors in parentheses. +$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

assessment of working memory emerged as the only significant predictor of reading progress status, controlling for age and HLLE. With each increase of 1 *SD* in working memory total score, children were 3.4 times more likely to be a high progressing reader. Results for stepwise logistic regressions are presented in Table 3.

Discussion

Identifying factors related to low progress in reading

The current study contributes new understanding to determinants of reading progress during a tablet-based literacy program implemented in a developing country. We found that children's working memory skills emerged as the only significant predictor of high compared with low reading progress, over and above age and a composite measure that broadly captured the quality of children's HLLE. These findings support prior research establishing working memory as a robust and consistent predictor of children's reading achievement (Pelegrina et al., 2015; Follmer, 2018; Peng et al., 2018). In addition, these findings corroborate recent work conducted in rural Côte d'Ivoire showing that a latent EF variable comprising working memory and inhibitory control emerged as the strongest predictor of children's literacy over and above other known predictors of literacy development, including home learning environment and age (Jasińska et al., 2022). Our study also sheds new light on the important role of working memory skills in supporting children's literacy development in a tablet-based program, specifically for children who show initial low literacy achievement prior to the intervention.

Findings from our study suggest that working memory skills may support children in benefiting from the format and content of a tablet-based literacy curriculum. Children with low working memory capacity have been shown to struggle with learning activities that place heavy demands on working memory (Alloway et al., 2009). The onecourse tablet-based literacy curriculum requires children to remember and apply instructions, while also processing, storing and updating information based on the learning content in in each unit. For example, in a unit that asks children to drag words to complete sentences, children have to remember the instructions (i.e., drag the word) while simultaneously reading the phrase (i.e., processing and storing) and identifying the word to complete the phrase (i.e., processing and updating information). As such, children who are more likely to forget instructions or have difficulty simultaneously processing, storing and updating information likely face greater challenges progressing accurately and efficiently through the curriculum. Indeed, recent work by van Uittert et al. (2022) that examined individual variation in responsiveness (i.e., in-game efficiency and accuracy) in a tablet-based word reading efficiency game intervention found that verbal working memory skills positively predicted in-game accuracy, which in turn related to first-grade children's growth in reading efficiency in the

Netherlands. This prior work examining the role of working memory in supporting children's reading progress in the context of a tablet-based program was conducted in a well-resourced country. The present study contributes new evidence to support working memory as a key factor in determining whether children who show initial low achievement in reading will benefit from exposure to a tablet-based literacy program in a developing context.

In contradiction to our hypothesis, we found that the quality of children's HLLE did not significantly relate to children's high versus low progress in reading. Bivariate correlations indicated that children who showed high versus low progress in reading did not differ significantly across any component that comprised the HLLE composite (i.e., presence of household reading materials, Bible, household literacy rates, radio or homework help). These findings are not in line with prior work showing positive associations between aspects of children's HLLE and reading progress (Nag et al., 2019; Friedlander, 2020) as they suggest that high and low progressing readers may come from homes with similar language and literacy supports, at least in our study community. Nonetheless, these non-significant associations between HLLE and reading progress status could also be due to limited sample power and thus should be interpreted with caution. Future empirical work should replicate these analyses to determine whether high versus low reading progress may relate to differences in the quality of children's HLLE in a larger sample of learners and in other developing contexts.

Implications for incorporating research-based strategies to support low working memory in tablet-based curriculum programs

Future interventions should consider incorporating baseline measures of working memory to identify learners who may struggle to fully benefit from exposure to a tablet-based literacy curriculum program. In addition, results from our study point to the importance of developing a wide-range of research-based strategies that can be used to improve content and delivery of the tablet-based software to better support learners who demonstrate low initial working memory skills. Indeed, evaluations of working memory training interventions have shown little evidence to suggest that only targeting improvements to children's working memory skills would be sufficient for producing better reading outcomes (Klingberg et al., 2005; Holmes et al., 2009; Bierman and Torres, 2016). In a two-year RCT, children screened as having low working memory skills and who participated in a computerized adaptive working memory intervention demonstrated only short-term improvements in visuo-spatial working memory and no benefits to other outcomes, including word reading (Roberts et al., 2016). Rather, these findings suggest that strategies for improving the software should incorporate multiple approaches that are designed to support low working memory skills, while also offering these learners opportunities to practice and learn strategies to strengthen these skills. Indeed, a recent review by Rowe et al. (2019) highlighted the effectiveness of interventions that rely on non-computerized strategies to target children's working memory skills in their everyday contexts. The review included one study that examined the effectiveness of two interventions in which teachers were trained to identify children who demonstrate working memory difficulties and then modify and reduce working memory loads for these children on instructional activities (Elliott et al., 2010). The interventions also showed teachers how to support the efficiency of these children's working memory skills by frequently repeating important information, encouraging the use of memory aids and teaching children to use memory-supporting strategies during their work (e.g., repeating key information out-loud or in their head). Together, these research-based strategies could offer guidance for individualizing content delivery for learners who show low working memory skills by reducing the content load of each unit (e.g., shorter units with simpler instructions), modifying instructions to repeat key information more frequently and explicitly teaching children strategies to help them remember learning content.

Further, evidence from prior work on tablet-based literacy interventions suggests that focusing on specific pre-reading skills, such as phonological awareness and letter knowledge, can improve reading achievement for struggling learners (Macaruso et al., 2006; Saine et al., 2011). Findings from a recent study indicated that exposure to an app that annotated text with phonemic images supported low achieving readers in accurately decoding pseudo words (Donnelly et al., 2020). In addition, van Uittert et al. (2022) showed that, among first-grade children who demonstrated a range of pre-literacy achievement, higher levels of specific reading precursors (i.e., phonological awareness, letter efficiency) related to higher in-game accuracy on a tablet-based reading intervention, which in turn predicted higher growth in reading efficiency. These findings are also consistent with research suggesting that targeting children's phonemic awareness can indirectly impact working memory (Melby-Lervåg and Hulme, 2010; Rowe et al., 2019). Motivated by the hypothesis that children's ability to recall words may depend on the quality of phonological representation of the word to be remembered, a study by Melby-Lervåg and Hulme (2010) showed that phoneme awareness training produced positive effects on verbal short-term memory. Together, these findings point to the importance of exploring whether providing targeted content to support critical pre-reading skills would promote higher reading outcomes for learners who demonstrate low pre-literacy and working memory skills.

Limitations and future directions

While results from our study offer new insights into factors that predict high versus low reading progress during a tablet-based literacy curriculum, we acknowledge several limitations of the study. Limited sample size prevented us from exploring how a wider range of factors may promote early literacy development in the context of a tablet-based program, such as children's school readiness and other learning behaviors. Future larger studies should explore how multiple factors may co-occur and influence children's reading trajectories.

In addition, more work is needed to further explore how factors associated with high versus low progress can be used to provide targeted, individualized support for learners who are at greater risk for non-progress due to low working memory and baseline literacy skills. While our study sample included learners who scored five total points or less on the baseline EGRA in a developing context, it is possible that the EGRA was not sufficiently fine-grained to detect differences in these learners' pre-reading skills. Based on recent work showing that higher pre-literacy skills can support children in optimally benefiting from a tablet-based reading program (van Uittert et al., 2022), future studies should consider incorporating a more sensitive diagnostic baseline reading assessment to better understand how small differences in reading precursors may contribute to patterns in children's reading progression, particularly in a developing context such as in Malawi where early grade illiteracy tends to be prevalent (World Bank, 2021).

More nuanced measures of children's pre-literacy skills could be used to individualize delivery of software content to target specific early literacy skills and thus better support at-risk learners' progress through the tablet-based literacy curriculum to promote higher reading progress.

We also relied on parent report on a small number of items to examine measures that broadly captured whether children were exposed to different aspects of literacy and language in the home environment. Future empirical studies should instead consider capturing more detailed information on the degree to which children experience the specific language and literacy practices in their home environment that have been shown to relate to reading achievement (e.g., family learning, parent competence in literacy and child interest in literacy; Friedlander, 2020).

Conclusion

Our study showed that working memory skills uniquely predicted high versus low progress in reading, controlling for other known determinants of early literacy development, among children who demonstrated low baseline literacy achievement. Given increasing evidence that tablet-based literacy interventions produce positive effects on literacy development in sub-Saharan Africa (Pitchford et al., 2017; Levesque et al., 2020, 2022), future work should continue to employ a comprehensive approach to exploring how multiple factors co-occur to promote or hinder children's reading progress in these programs. Further, as educational technology programs continue to proliferate in developing countries, research that can offer evidence-based strategies for supporting learners who are at risk for non-progress in reading will be critical to ensure that these programs can meet the educational needs of diverse types of learners.

Data availability statement

The datasets presented in this article are not readily available because we are not currently sharing data for this study. Requests to access the datasets should be directed to corresponding author.

Ethics statement

This study involved human participants and was approved by Research Ethics and Regulatory Approval and Permit for Protocol (P08/21/77), which was obtained from University of Malawi Research Ethics Committee. Per the 2019 University of Malawi Research and Ethics Committee (UNIMAREC) Guidelines, oral/verbal consent can be obtained in the case of potential participants who do not read or understand the language of the written consent form. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

KL, SB, AC, and CL designed and conducted the study. KL, SB, and CL analyzed the data. SW processed ethical approval and managed data collection for the study. SB wrote the article. All authors reviewed and commented on the final article text.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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