International Journal of Innovation in Science and Mathematics Education, 30(5), 1-19, 2022

Learning Mathematics with Interactive Technology in Kenya Grade-one Classes

Larysa Lysenko[a], Philip C. Abrami[a], Anne Wade[a], Enos Kiforo[b], and Rose Iminza[b]

Corresponding author: Larysa Lysenko (larysa.lysenko@concordia.ca)
[a]Centre for the Study of Learning and Performance, Concordia University, Montreal, Quebec H3G 1M8, Canada
[b]Aga Khan Academy, Mombasa, Kenya

Keywords: educational technology, primary mathematics, student achievement, Kenya, Africa

Abstract

While countries in sub-Saharan Africa have made significant progress towards achieving universal school enrolment, millions of students lack basic numeracy skills. This paper reports the results of a pilot study that aimed at using the Emergent Literacy in Mathematics (ELM) software to teach mathematics in early primary grades in Kenya. Designed as a pre- and post-test non-equivalent group research, the study unfolded in 14 grade-one classes from 7 primary public schools. After having learned with ELM for about two terms, the experimental students ($N = 283$) considerably outperformed their peers ($N = 171$) exposed to traditional instruction with the effect sizes of $+0.37$ on the overall skills measured by a standardised test of mathematics. The impact of ELM activities was the greatest on students' ability to take language and concepts of mathematics and apply appropriate operations and computation to solve word problems. On this set of skills, the magnitude of difference between the experimental and control groups was $+0.77$. This study also revealed some positive shifts in the teachers' perceptions about their practice. The teachers who adopted ELM in their practice reported having gained more confidence in mathematics and comfort in teaching mathematics with computers.

Introduction

Together with literacy, Science, Technology, Engineering and Mathematics (STEM) education plays a critical role in driving countries' economic growth and is a stable source of innovation-driven employment (National Research Council, 2011). Mathematics attainment has been noted for the important impact it has on individual income potential across the economic contexts, either advantaged (Hanushek, Schwerdt, Wiederhold, & Woessmann, 2015) or disadvantaged (Dickerson, McIntosh, & Valente, 2015). Despite the promise, the road to quality mathematics education has been bumpy and especially so for the low- and medium-income countries (LMIC). While these countries made significant progress towards achieving universal school enrolment, millions of students lack foundational skills (including mathematics), even though they spend years in primary school (World Bank, 2018). For instance, in sub-Saharan Africa, by the end of primary, less than one-third of students can solve a simple two-digit subtraction problem and only one in five students have the second-grade mathematics skills (Uwezo, 2016).

Large classes, insufficient resources, and lack of qualified mathematics teachers remain the major challenges hindering the quality of mathematics education (Tikly et al., 2018). With computer technology becoming cheaper and increasingly wide-spread, education stakeholders view it as a solution to address the challenges in the contexts where the demand for quality resources is high. Encouragement also comes from educational research confirming the potential of educational technology to improve primary students' mathematics achievement (e.g., Chauhan, 2017) and enhance teaching (e.g., Bray & Tangney, 2017). Hence, there is a growing number of government-supported initiatives, such as DigiSchool in Kenya, UConnect in Uganda, and SchoolNet in Ethiopia to name a few. These and other ICT-based educational initiatives in African countries are overviewed in the IST-Africa Consortium report (2018).

This paper reports the results of a study in Kenya where an interactive mathematics software is being used to support primary teachers' use of effective instructional strategies to improve their students' learning of mathematics.

Study Background

Early mathematics instruction

Instruction of foundational mathematics skills has been studied substantially. The findings of this research are reflected by the widely accepted instructional principles (National Council of Teachers of Mathematics [NCTM], 2014) suggesting that effective teaching develops students' understanding of concepts and connects this understanding to computational methods and strategies in their application to solve mathematical problems. Effective instruction instils both students' procedural fluency as flexibility to choose adequate computational strategies and methods and capacity to produce accurate answers efficiently, and procedural mastery, ability to instantly recall arithmetic procedures and to carry them out automatically. The combination of these two skills reduces cognitive load and frees up memory resources that can be used to monitor performance and to learn more complex procedures. For instance, in primary mathematics, gaining fluency and mastery of such aspects of number concept as cardinality and ordinal relationships between numbers, enables the student to proceed from concrete to abstract, reaching the ability to carry out mental computation. Such progression requires students' understanding of single-digit whole numbers, their magnitude, the relationships between them, and working with patterns. Developing automaticity of operations with single-digit numbers is critical, as these operations form the basis of all numerical procedures (e.g., Baroody & Purpura, 2017). Because students remember them better and use them more flexibly, students can think about other aspects of a problem and tackle new kinds of problems, which then leads to new understanding (Fuson, Kalchman, & Bransford, 2005; Codding, Mercer, Connell, Fiorello, & Kleinert, 2016).

Since students' acquisition of new mathematical ideas depends on their prior knowledge (e.g., Anthony & Walshaw, 2007), effective instruction is also differentiated. It frequently assesses what students understand and can do mathematically, and then responds to an individual student's strengths and weaknesses enabling her to proceed at her own level of understanding (NCTM, 2014). Hence, no one practice can dominate across all settings and learners. Clements, Fuson, and Sarama (2017) argue for a "balanced approach" to teaching mathematics that is based on the learning trajectories providing guidance for developmentally appropriate mathematical experiences and helps all students achieve mathematics proficiency. Specifically, the benefit of balanced instruction lies in the teacher capacity to combine procedural (basic skills acquisition and calculation activities) and conceptual (development of analytic and reasoning skills) instruction as a student develops more skills and advances in her learning (Heatly, Bachman, & Votruba-Drzal, 2015). Further, the relevance of precision teaching has been brough in as the teacher's ability to determine what method of instruction is appropriate at a specific point on a student's learning path (e.g., Hattie, 2017).

Systematic evidence suggests that computer technologies can reinforce student-centeredness in mathematics instruction. When used as a differentiation tool, computers produce small to moderate positive effects on students' performance (Deunk, Smale-Jacobse, de Boer, Doolaard, & Bosker, 2018). The effects are large when computer technology is used for learning in small groups and constructivist instruction (Li & Ma, 2010). When it supports problem-solving processes, computer instruction benefits low-performing students (Ran, Kasli, & Secada, 2021). The effects of computer instruction are also noticeable on student motivation to learn mathematics (Higgins, Huscroft-D'Angelo, & Crawford, 2019). Of the entire student population, it is primary students who benefit the most from learning mathematics with technology. This promising evidence, and also considerable improvements in connectivity and accessibility of devices, explain the increasing enthusiasm that medium- and low-income nations show about using computers for early mathematics instruction (Platas, Ketterlin-Geller, & Sitabkhan, 2016).

Primary curriculum and mathematics instruction in Kenya

Although research indicates what effective teaching of early mathematics looks like (e.g., Cheung & Slavin, 2013; Hattie, 2017), questions remain about how best to implement these approaches, especially in the context of less affluent countries. Among the broad range of challenges at the school, household, community, and national levels, many relate to the quality of mathematics instruction, including lack of adequate instructional materials and insufficient teaching capacity (e.g., Akyeampong, 2019; Bethall, 2016; World Bank, 2018). For instance, reported by Bold et al. (2017) the Service Delivery Indicators from six Sub-Saharan countries indicate that 40 percent of primary teachers were not as knowledgeable in mathematics as their students should be by the end of primary school cycle. Few teachers demonstrated capacity to engage in the effective instructional practices such as assessing student's abilities and learning progression, asking questions, and providing feedback.

In Kenya, the scarcity of quality mathematics instruction has been documented (e.g., Barasa, 2020; Ngware, Ciera, Musyoka, & Oketch, 2015). To address the issue, the Kenyan government has implemented the Primary Education Development (PRIEDE) initiative across the nation's public primary schools. With the particular focus on early-grade numeracy, PRIEDE is hoped to enhance the country's ongoing competency-based curriculum reform (CBC) and capitalise on the government-funded Digital Learning Program (DLP, also known as DigiSchool). The latter targets integration of information and communications technology (ICT) in primary school teaching and learning by distributing devices to schools, improving school infrastructure, developing digital content, and building teacher computer capacity (ICT Authority, 2016).

PRIEDE's strategic components include provision of requisite early grade mathematics materials to teachers and students, building the mathematical capacity of teachers, and supporting their practice. The content of student textbooks and teacher guides is organised in strands and grade-specific sub-strands. For instance, in grade one, the 'number strand' includes number concept, whole numbers from 0 to 100, addition, and subtraction, whose teaching takes around 60% of the instructional time. Student mastery of numbers by tackling problems related to day-to-day life is the expected outcome. Being paper-based and prescriptive, the instructional materials promote the instructional strategies of teacher demonstration and guidance, and classwork where students are required to complete worksheets (e.g., Ministry of Education [MoE] Republic of Kenya, 2016). Some PRIEDE materials in static, flat format are accessible on the DLP devices.

In addition to supplying instructional materials, national teacher training was rolled out, and the structures of pedagogical support to teachers were established. The national training documents (e.g., MoE Republic of Kenya, 2018) suggest a strong focus on developing teachers' understanding of the early grade mathematics content, whilst giving some consideration to the instructional strategies, such as differentiated learning and integration of technology. Curriculum support officers observe instruction and support teachers during classroom visits, whereas school headteachers exercise supervision and quality assurance of implementation. The program was heralded successful – all public primary schools received basic teaching and learning materials, as well as training in Early Grade Mathematics methodology (Rawal, Aslam, & Outhred, 2019). However, national research indicates that teachers are inadequately prepared, and thus unable to teach and evaluate the new curriculum programmes (e.g., Kisirkoi & Kamanga, 2018; Momaniy & Rop, 2020). In their endline evaluation of PRIEDE, the Kenyan National Examination Council's report (KNEC, 2020) suggests numerous gaps. For instance, KNEC positions that most of the teachers received sufficient training. Yet, the quality and amount of training may not be satisfactory; only 23 percent of respondents qualify this training as useful but to limited extent. Teaching remained largely frontal, where nearly 40 percent of teachers were observed to commonly use a 'lecture method' to teach mathematics in primary classes. Important issues were reported about teaching with computers too. Even though 1.2 million DLP devices were distributed to primary schools, only 22 percent of teachers reported having used these devices with some consistency to teach early grade mathematics. Training in computer pedagogy was reported insufficient; only 54 percent of teachers were trained on how to use ICT for teaching mathematics. A significant void of digital interactive learning content within the DLP ecosystem was also reported (UNESCO Mahatma Gandhi Institute of Education for Peace and Sustainable Development, 2019).

In this context, we conducted a pilot study targeting teachers' use of mathematics interactive software in grade-one primary classrooms in Kenya. We developed an intervention, incorporated it into the authentic context of public schools, and examined its impact upon classroom instruction and student mathematics skills. While exploring the potential of the software to be effective for primary mathematics instruction in Kenya, we addressed the following questions:

- How does the software implementation impact grade-one students' mathematics competencies?
- Do the effects vary across student characteristics (such as gender and baseline achievement)?
- What are the impacts of the intervention (including the software and associated professional development and support) upon the instructional practices of Kenyan mathematics teachers?

Method

Research design

This study is designed as a non-equivalent control group pre- and post-test. While the intervention unfolded in the experimental classes, students in the control classes were exposed to their usual mathematics instruction. Student and teacher data were collected twice within an eight-month interval: first, before the implementation started, and then, at the conclusion of the intervention. The data from students and teachers were collected by the local teachers trained in the administration of the instruments. The details on data collection instruments and analytical strategies are presented in the Instruments section of this manuscript.

Study sample

Seven public schools with comparable socio-economic characteristics from the Mombasa area were recruited to be part of either the experimental or control group. In the experimental group, 9 teachers and their 358 students used the software as part of their mathematics instruction. In the control group 5 teachers taught mathematics to their 255 students in a usual fashion. Some students missed either the pre-test or post-test due to illness or changing school. Therefore, the data for 283 experimental and 171 control students were analysed.

The class sizes varied from 28 to 61 students with an average size of 41 students in the experimental class and 50 students in the control class. The gender splits within the groups were about equal, with approximately 56 percent of boys and 44 percent of girls.

Teachers in both groups were comparable regarding mathematics training and teaching experience. All but one teacher received some certification either from university or teacher training college. The teachers had taught between three to 34 years, with an average of 21 years of experience.

Emergent Literacy in Mathematics (ELM) Intervention

ELM software

ELM is engaging software offered within the Learning Toolkit Plus, a collection of evidence-based learning tools (http://www.concordia.ca/research/learning-performance/tools/learning-toolkit/elm.html). The software is designed to promote the development of young children's foundational skills in mathematics as described by the NCTM (2014).

The design of ELM draws on the current evidence showing promising links between mathematics instruction and computer technologies (e.g., Li & Ma, 2010). The design is also based on the multimedia design principles (e.g., Mayer, 2008) aiming at reducing cognitive load, engaging learners, decreasing anxiety, scaffolding understanding, and proficiency building.

The ELM content is structured using Themes (overarching branches of mathematics), which are divided into Ideas (mathematical concepts). Figures 1 and 2 illustrate the ELM content structure. To build students' understanding of a concept, each Idea then follows a set of carefully sequenced activities that move from concrete to more abstract, from images and physical actions to mental images and symbolic representations.

Figure 1. ELM splash page

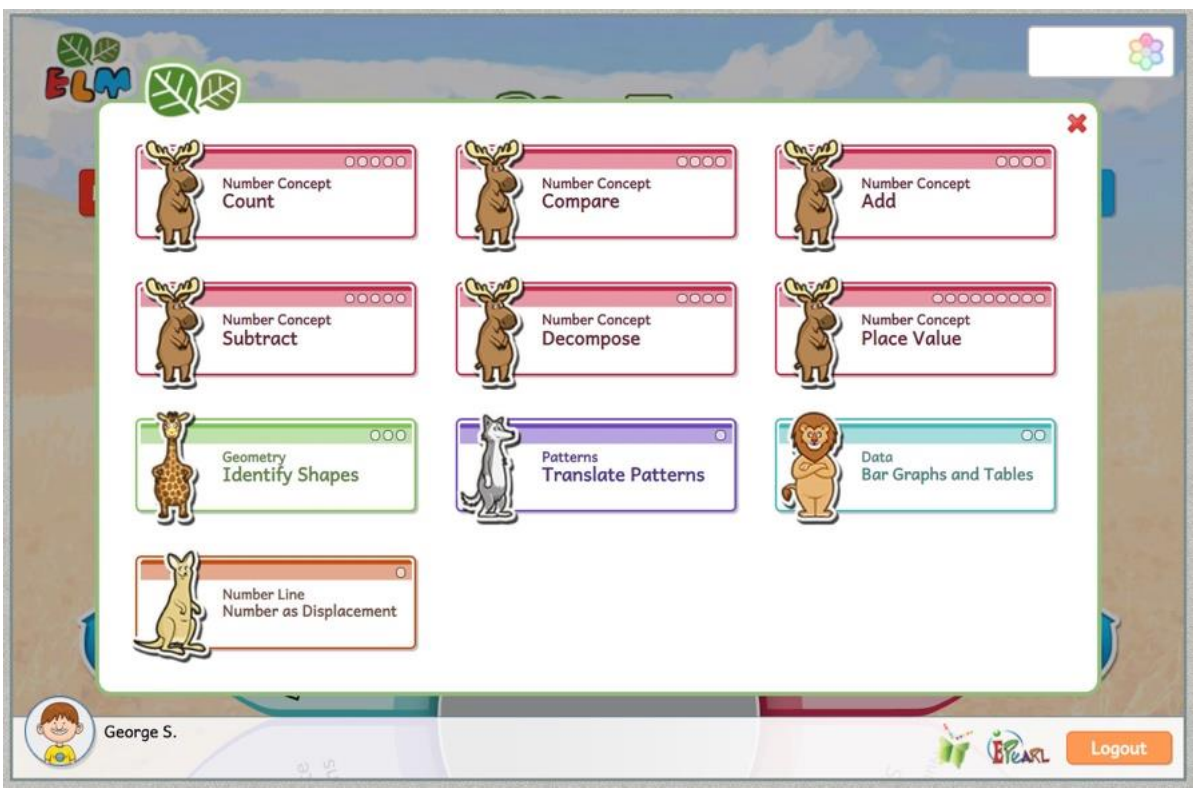

Figure 2. ELM Themes and Ideas

For example, initially, a student is asked to count by performing the equivalent of touching the image of each object, then by generating a mark corresponding to each object being counted, and finally, by counting in their head and reporting that count using number symbols. Each activity is presented as a jigsaw puzzle (Figure 3) having some missing puzzle pieces, where each piece represents a set within the activity. The activity is completed once the student acquires all the missing puzzle pieces. The 38 activities focus on: Number Concept (Count, Compare, Add, Subtract, Decompose, Place Value); Geometry (Identify shapes); Patterns (Translate patterns); Data (Bar graphs and tables); and Number Line (Number as displacement).

Figure 3. Example of an ELM Puzzle

To encourage student autonomy, ELM offers a system of embedded help and supports. This includes audio and visual feedback to the students as they complete activities at their own pace, guiding them to the correct answer. Demonstrations are integrated within each phase of an activity to avoid overwhelming students, and all activities have a ‘help’ button to provide built-in ‘just-in-time’ support.

For instance, Figure 4 offers an example of the help features that the student can get from ELM by clicking on the following icons: speaker -- repeats the instruction; question mark -- provides context-sensitive help on the step; film -- plays a demo of the step.

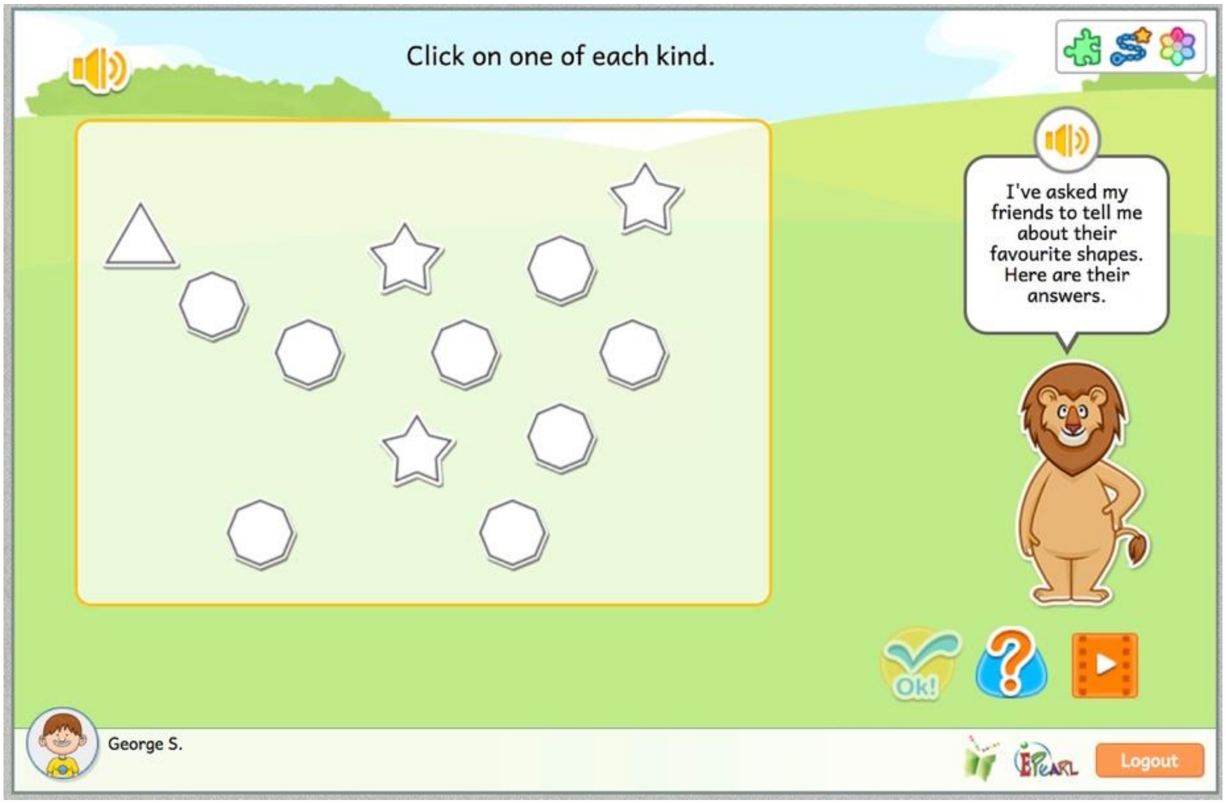

Figure 4. ELM Embedded Help Features

The teacher interface in ELM offers a collection of multimedia resources designed to help teachers use the tool (https://literacy.concordia.ca/resources/elm/teacher/en/structure.php). These resources accompany each activity within the tool including information on that activity, detailed lesson plan with learning objectives, an extension activity and a reflection exercise. Video demos and recommended external resources such as online math games, are part of teacher resources.

The ELM report is a teacher tool that generates an overview of the progress of a whole class or a single student. For example, it shows whether the student eventually completed a particular activity, or if the student had trouble at some point in the activity. To differentiate instruction, ELM allows teachers to set a plan for a student or groups by adjusting the number of repetitions required in any given activity, or by assigning an additional 're-do' for any activity. If a student has been assigned a specific plan, the ELM report displays the settings of the plan and the student's progress through it.

The ELM software passed its initial validation in Canada, revealing impacts on grade-one students' mathematics achievement (Lysenko et al., 2016). Having learnt with ELM for about one term, experimental students outperformed their peers who were exposed to traditional instruction. The effects of ELM were also observable on a set of affective outcomes; the students reported more enjoyment from learning mathematics, and less anxiety and boredom.

ELM intervention

The integration of ELM in mathematics instruction was at the heart of intervention. The implementation took from 10 to 14 weeks between January and September of 2019 in school computer laboratories. Students were expected to be exposed to ELM instruction for one hour per week, but it was often less. The devices were desktop computers, government-provided tablets, or some combination of both. Students had to do their computer work in pairs or in groups of three or four.

To ensure adequate integration of the software into classroom instruction, professional development was offered to the experimental teachers. They were trained on the ELM software and its pedagogy at a one-day training workshop. This was followed by three half-day out-of-school follow-up sessions held once per term. In-school support to the experimental teachers was provided by an external expert teacher (Ambassador) and a school-based ambassador (SBA), who was a specially trained teacher in each school that participated in the study. The SBA facilitated in-school planning meetings with their teachers, scheduled access to the computer laboratory, and sometimes assisted teachers during ELM instruction. To complement the efforts of SBAs, external Ambassadors gave between three to five visits to the assigned classes, where they observed classes and assisted with instruction. These visits were held on the days when teachers came for in-school planning, where among other topics, teachers worked on differentiated instruction.

A set of ELM instructional materials was offered to teachers, including the ELM curriculum developed expressly to align the use of the tool with the Kenyan grade-one mathematics curriculum. The supplementary pedagogical materials also included lesson plans, classroom activities, and job aids, and print-based ELM extension activities. The implementation strategies and the use of materials and resources were suggested, but their integration was left entirely at the teachers' discretion.

Instruments

Student achievement measures

The change in the students' mathematical skills was measured using the *Group Mathematics Assessment and Diagnostic Evaluation* (GMADE) Level 1 (Williams, 2004), a commercial, group-administered, standardised test of mathematical achievement. To collect pre- and post-data, parallel paper-and-pencil forms (A or B) were used respectively. This level covers the 6 to 11 years old age band, by offering items at a wide range of difficulty, allowing for measurement of low-, average- and high-performing students. Eighty items pertaining to content-driven categories, such as algebra, comparison, geometry, measurement, money, numeration, quantity, sequence, statistics, and time are grouped into three sub-tests:

- *Concepts and Communication* (28 items) – addresses the language, vocabulary, and representations of mathematics, and contain symbols, words, and phrases that fit the content-driven categories.
- *Operations and Computation* (24 items) – evaluates the ability to use basic operations of addition and subtraction (in both vertical and horizontal forms), with a variety of mathematical representations.
- *Process and Applications* (28 items) – measures the students' ability to take the language and concepts of mathematics and apply appropriate operation(s) and computation to solve a

word problem that fits the content-driven categories. These are one-step, single-operation problems except for one which is a multiple-step problem.

Teacher measures

The *Mathematics Teacher pre- and post-surveys* were used to collect information from control and experimental teachers about mathematics instruction (https://www.concordia.ca/research/learning-performance/knowledge-transfer/instruments.html). The purpose of these 10-minute surveys was to elicit teacher reflections about their practices in teaching mathematics to grade-one students, including their use of technology. Specifically, the questions related to grade-one mathematics curriculum (PRIEDE), level of confidence in teaching early mathematics, availability and reliability of school technology, and level of comfort in teaching with technology. The post-test survey also asked experimental group teachers about their experience in teaching with ELM, including the level of in-school support they received.

Analyses

Student and teacher data were entered into *SPSS 26* for Mac OS X and verified for accuracy. After merging student pre- and post-test data, the datafile contained 613 cases. The data of 454 students who completed both tests were analysed. The data did not deviate from normality; the indices of skewness and kurtosis ranged from -2.5 to 2.8. The composite scores were calculated along the three GMADE sub-scales and Total scale.

The initial difference between the groups had been detected on the GMADE pre-test ($F(1,453) = 3.85, p = 0.05$), thus the Repeated Measures Analysis Of Variance (RM MANOVA) was used. The basic one-way model included testing time (pre- and post-test) as the within-subject variable and treatment (ELM vs. no-ELM) as a between-subject factor. Two supplementary MANOVA analyses were run where student gender and initial mathematics ability were used as between-subject factors. We also report mean scores and standard deviations as well as standardised effect sizes (i.e., Cohen's d) by group. The latter were calculated as the mean difference between the two groups' pre- and post-test score change, divided by the pooled standard deviation. Teacher self-reported data are presented in a qualitative summary.

Results

Student results

A summary of student achievement scores on each of the GMADE sub-tests is presented in Table 1. The data suggest that students in both groups improved over time with important benefits to the ELM students.

Table 1. Grade-one students' mathematics achievements: group means, standard deviations, gains, and standardised effect sizes.

	Concepts and Communication (max 28)		Operations and Computation (max 24)		Processes and Application (max 28)		Total Test (max 80)	
	Post	Pre	Post	Pre	Post	Pre	Post	Pre
Experimental group	19.90	16.63	16.83	12.92	15.45	10.57	52.18	40.12
($N = 283$)	*4.02*	*3.74*	*5.37*	*5.68*	*3.73*	*4.735*	*10.81*	*11.02*
Change scores	3.27		3.91		4.88		12.06	
Control group	18.44	16.22	15.15	11.65	12.8	11.02	46.39	38.89
($N = 179$)	*5.13*	*5.65*	*6.77*	*5.87*	*4.47*	*3.39*	*14.19*	*12.63*
Change scores	2.22		3.50		1.78		7.50	
Effect size (Cohen's d)	*0.23*		*0.07*		*0.77*		*0.37*	
Male experimental students ($N = 150$)	20.05	16.67	16.65	13.43	15.64	10.37	52.34	40.47
	4.09	*3.68*	*5.17*	*5.64*	*3.63*	*4.59*	*10.74*	*10.93*
Change scores	3.38		3.22		5.27		11.87	
Male control students	18.01	15.59	13.95	11.21	11.82	10.89	43.78	37.69
($N = 98$)	*5.32*	*5.49*	*6.68*	*5.38*	*4.54*	*3.38*	*14.37*	*12.26*
Change scores	2.42		2.74		0.93		6.09	
Effect size (Cohen's d)	*0.21*		*0.08*		*1.08*		*0.47*	
Female experimental students ($N = 133$)	19.74	16.58	17.02	12.35	15.23	10.8	51.99	39.72
	3.94	*3.82*	*5.59*	*5.69*	*3.84*	*4.9*	*10.92*	*11.15*
Change scores	3.16		4.67		4.43		12.27	
Female control students ($N = 81$)	18.96	16.98	16.59	12.19	13.99	11.17	49.54	40.33
	4.87	*5.79*	*6.63*	*6.40*	*4.1*	*3.42*	*13.38*	*12.99*
Change scores	1.98		4.40		2.82		9.21	
Effect size (Cohen's d)	*0.27*		*0.04*		*0.41*		*0.26*	
Experimental low performers ($N = 97$)	18.64	13.69	13.78	7.54	14.55	7.14	46.97	28.37
	3.93	*3.02*	*5.36*	*2.99*	*4.20*	*2.87*	*11.16*	*4.28*
Change scores	4.95		6.24		7.41		18.6	
Control low performers ($N = 67$)	15.57	11.72	10.58	6.48	10.39	8.09	36.54	26.28
	4.92	*3.24*	*5.60*	*2.91*	*3.42*	*2.57*	*11.05*	*4.91*
Change scores	3.85		4.1		2.30		10.26	
Effect size (Cohen's d)	*0.25*		*0.39*		*1.31*		*0.75*	

The RM MANOVA Pillai's trace criterion ($F(3{,}450) = 14.72, p = 0.000$), indicates statistically significant difference between experimental and control students' change scores on a combined set of GMADE sub-tests over time. The partial eta-squared of 0.088 confirms the difference. The univariate tests reveal the significant effects of ELM on the experimental students' mathematical skills, measured on the sub-tests of Concepts and Communication ($F(1{,}452) = 5.95, p = 0.015$, partial $\eta^2 = 0.013$) and Process and Applications ($F(1{,}452) = 42.76, p = 0.000$, partial $\eta^2 = 0.085$). On the scale of Operations and Computation, the groups did not differ significantly. Positive standardised effect sizes (Cohen's d) echo the above results and indicate the most important effects of ELM upon the students' ability to solve mathematical problems. On this set of skills, the experimental students outperformed their control peers by 0.77 standard deviation (Table 1).

Figure 5 illustrates the change of the students' mean GMADE Total scores by group with confidence intervals set at 95%. Points are offset horizontally so that the error bars representing confidence intervals are visible. The dashed lines connecting mean scores do not suggest that linear growth happened from pre- to post-test.

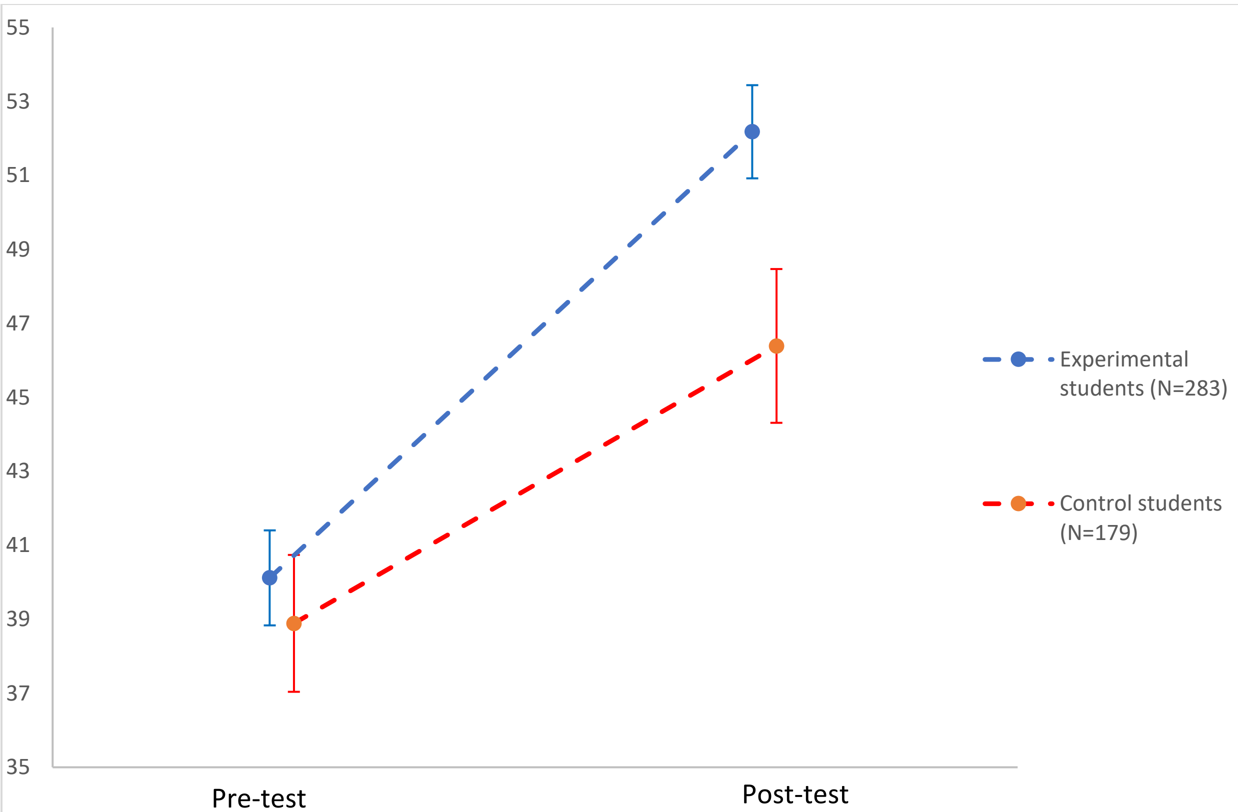

Figure 5. Total GMADE score changes (means, 95% confidence intervals) by group.

As a next step we explored if ELM effects vary as a factor of student gender. The analyses suggest that in addition to the treatment effect, student gender accounted the difference between experimental and control students' mathematics skills from pre- to post-test ($F(3{,}448) = 3.25, p = 0.022$, partial $\eta^2 = 0.021$). The univariate results indicate that the experimental students of both genders gained more than their peers in the control group, with the statistically significant difference on the scale of Process and Applications ($F(1{,}450) = 8.37$, $p = 0.004$, partial $\eta^2 = 0.018$).

The variation of gain scores between boys and girls from both groups on the GMADE total test is reflected in Figure 6. For the visibility of the error bars representing confidence intervals, points are offset horizontally. The dashed lines do not suggest that growth of mean scores from pre- to post-test was linear. The ELM instruction minimized the difference between students of both genders. The control students' gains were significantly smaller than those of the experimental students of both genders. Furthermore, the gap between control male and female students grew larger at the conclusion of the study.

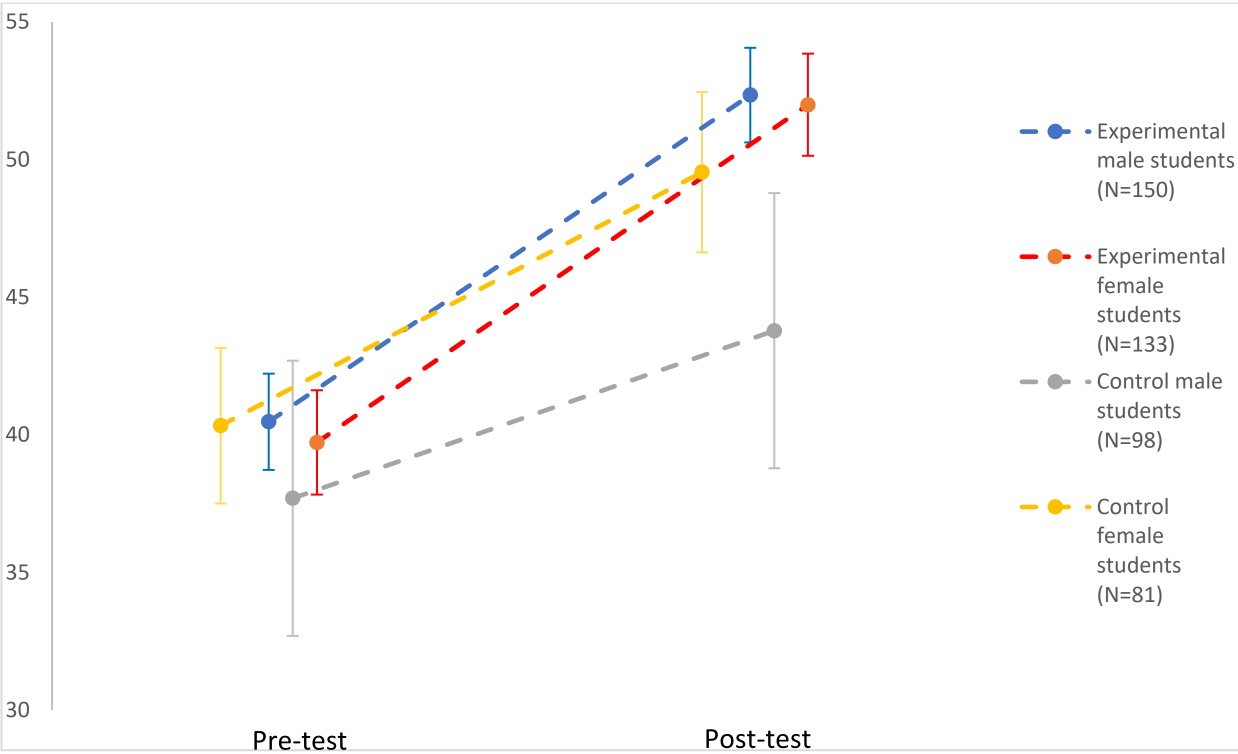

Figure 6. Total GMADE change scores (means, 95% confidence intervals) by group and gender.

Lastly, we explored whether the effects induced by the ELM software may vary as a function of student pre-test mathematical ability differences. The students of low mathematical ability scored below 34 points on the pre-test and were about 30% of students from both groups ($N_{\text{experimental}} = 97$; $N_{\text{control}} = 67$). The comparison of their pre-post gains reveals statistically significant differences between low performing students from experimental and control groups on the GMADE measure of mathematical ability ($F(3{,}160) = 17.34$, $p = 0.000$, partial $\eta^2 = 0.246$). Univariate tests indicated statistically significant differences between the groups on the sub-tests of Operations and Computation ($F(1{,}162) = 4.68$, $p = 0.029$, partial $\eta^2 = 0.03$), and Process and Applications ($F(1{,}162) = 52.17$, $p = 0.000$, partial $\eta^2 = 0.24$).

Figure 7 illustrates the improvements of low mathematics ability students in the experimental and control groups. Points are offset horizontally so that the error bars representing confidence intervals are visible. Linear growth of the mean scores from pre- to post-test is not assumed.

As a result of ELM instruction, the low mathematics ability students made significant progress towards catching up with the average mathematics ability students from the experimental group.

The improvements over time of the control students were less prominent, and the gap separating the low mathematics ability students from both groups grew significantly larger at the post-test. It is important to note that for the sub-sample of low mathematics ability students, ELM effects were consistently the largest on all GMADE measures. Table 1 shows that the highest effect was on the Process and Applications sub-test, where the low mathematics ability experimental group students outperformed their control peers by 1.31 standard deviations as measured by the Cohen's d.

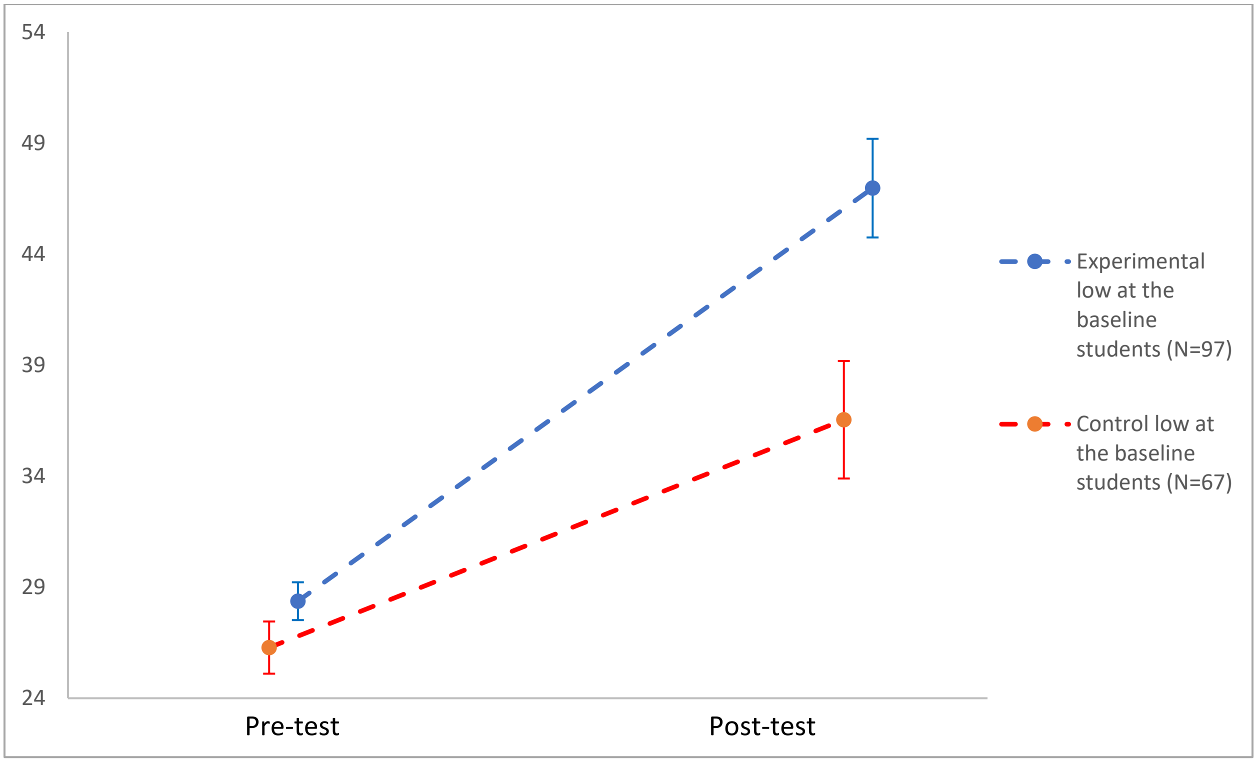

Figure 7. Total GMADE change scores (means, 95% confidence intervals) for struggling students by group.

In summary, all the analyses yielded consistently positive effects of ELM on the four learning outcomes captured by the standardised assessment of mathematics ability. All grade-one students who learned mathematics using the software for over two terms outperformed their peers in the control group. The effects of learning with ELM were noticeable for the students of both genders, and particularly important for those struggling with mathematics.

ELM instruction

To learn about the practice of mathematics instruction in ELM and control classes, we collected teacher surveys. Since only 8 of the 14 teachers completed them both at pre- and post-test leaving few points for quantitative data analyses, we present them as a qualitative summary.

The self-reports of nine experimental and five control teachers indicated that computer technology was available in each participating school. School computer laboratories were supplemented with a set of government provided DLP tablets. Yet, at the onset of the study, a quarter of the teachers in both conditions reported their students having no access to school computers. Around 70% of teachers described classroom devices as reliable. With the average ratio of 2.5 students per computer, about 35% of teachers stated that there were enough of them for the entire class. Issues with electricity were reported by 40% of control and 17% of experimental teachers. None of the schools had electricity generators to make up for interruptions.

The pre-test surveys revealed that more experimental group teachers reported feeling comfortable in their abilities to teach with computers (56%) than their control colleagues (20%). Meanwhile, all five control teachers expressed confidence in teaching early mathematics compared to about half of the experimental teachers. Regarding the mathematics content, all the teachers consistently reported counting as the concept they taught to their grade-one students. Most teachers also reported teaching comparing, subtracting, and adding whereas none of them taught decomposing.

From pre- to post-test, there were noticeable improvements in six experimental teachers' perceptions of their own confidence in mathematics, as well as their comfort in teaching mathematics with computers. For instance, 83% reported that their level in teaching early mathematics as "confident", and ability to use computers for instruction as "very comfortable". All teachers reported becoming comfortable in teaching mathematics with ELM too. In addition to the content reported at the pre-test, ELM was used to teach place value, patterns, decomposing and geometry. All six teachers reported having received in-school support on how to integrate ELM in mathematics instruction and being satisfied with it.

Discussion

This study features the evaluation of a technology-based mathematics intervention implemented in Kenyan public primary schools by regular teachers. The strengths of this study include a comparison group pre-selected to be similar with the experimental group, using standardised testing of students' mathematical abilities before and after the intervention, accounting for the students' gender and their initial mathematical ability. The limitations of the study emanate from the study's quasi-experimental design. Inequivalence between the groups relating to the initial differences among the students, may pertain to their teachers too. Experimental teachers might have been more open to innovative teaching practices, or have been more enthusiastic teachers in general, than their control counterparts. Establishing the link between the instruction and students' learning gains overtime was not possible because of the small number of teacher-participants and their missing self-reports.

Despite the limitations, the overall effects of classroom uses of ELM on grade-one students are evident. All students learned mathematics regardless of gender, or initial abilities. The gains are notable in both basic and complex skills. For instance, on problem-solving tasks, ELM students outperformed their control peers by 28 percentile points. Students had to understand a word problem read aloud to them, then to apply an appropriate strategy to solve it and to reason and estimate an answer that makes sense. The value of developing skills of strategising a solution to the problem cannot be underestimated as they serve students in everyday life situations.

In the context where significant gender discrepancies in mathematics achievement emerge by the beginning of second grade (Pitchford, Chigeda, & Hubber, 2019), the improvements in mathematical ability of boys and girls who learnt with ELM is another notable finding. The ELM instruction not only prevented the initial gender disparity of mathematics skills from growing but reduced it to the negligible level.

The important gains of struggling ELM students may suggest that using ELM software may help reverse the so-called “Matthew’s effect”, implying the widening gap between high- and low-ability students as they progress through schooling (Stanovich, 2009). This finding is also notable in the context of evidence from developing countries indicating that students with stronger baseline skills may gain more from using technology than their struggling peers (e.g., Kim, Boyle, Zuilkowski, & Nakamura, 2016).

The above effects of ELM can be explained, in part, by its design informed by research on instructional multimedia and effective mathematic instruction. For instance, application of evidence-based principles (e.g., Mayer, 2008) allowed for reduction of extraneous elements in the software, supporting working memory with learner-paced segments, and use of both verbal and visual modes of representation. The tool’s interactive multimedia illustrate key mathematical concepts in an engaging and readily understandable fashion for young learners. The progressive difficulty of the ELM tasks ensures that students advance through the key mathematical concepts, at a pace appropriate for their prior achievement and understanding. These and other features of the software make it a relevant learning tool in contexts where teaching often equates teacher-centred frontal instruction, and the curriculum-aligned digital content is mostly a static duplication of textbook (UNESCO, 2019).

However, ELM is not a substitute for classroom instruction; instead, it is designed to support the efforts of mathematics teachers. The tool provides the scaffolding that teachers need to ensure they both cover the curriculum, and deliver the concepts to students, accurately and confidently. The ongoing in-school support was offered to teachers as they experienced the benefits and challenges of using ELM to teach regular mathematics lessons. The teachers were autonomous in making decisions about how and when to integrate the tool into their instruction. Over time, they reported having gained more confidence in mathematics and comfort in teaching it with computers. Despite this, our knowledge about how ELM influenced teachers and their practice remains subtle. For example, we do not know if the teachers used the tool because students could be assigned to work independently (e.g., Grimalt-Álvaro, Ametllerb, & Pintóa, 2019). Or the teachers might have chosen to use ELM for its learner-centred design and, thus, felt that their teaching became more aligned with the new national curriculum without significantly changing their instruction. It might also be that these shifts suggest an initial step towards deeper improvement in instructional practices, such as those reported by Crook, Sharma, and Wilson (2017) implying move towards a genuine learner-centred approach where the software is integrated in instruction, not simply added on during a computer session.

In this regard, we are yet to learn what aspects of ELM intervention enable teachers to embrace pedagogical sophistication offered by the tool. In the future study, we will establish models of successful ELM integration, hence adding value of this research for educational practice. Finally, we will investigate how to ensure the innovation longevity and how to go beyond scattered pockets of use, extending opportunities for quality mathematics education for more primary students.

Acknowledgments

This work was undertaken with the financial support from the Social Sciences and Humanities Research Council (SSHRC) of Canada and International Research and Development Centre (IDRC). It has the approval of the Concordia University human research ethics committee # 10000298.

We would like to acknowledge the important contributions of professors Steven Rosenfield and Helena Dedic in the design of ELM and support materials. We also thank the LTK+ African Coordinator, Dr. Maina WaGioko, whose wise guidance and contributions to the professional development and support of the teachers helped this project to succeed. Finally, we express our gratitude to the Ambassadors who worked alongside our professional development team in Mombasa to help train and support teachers in their use of ELM.

References

Akyeampong, A. (2019, July). *Improving teaching and learning. A Knowledge and Innovation Exchange Discussion Paper*. https://www.globalpartnership.org/content/improving-teaching-and-learning-knowledge-and-innovation-exchange-kix-discussion-paper

Anthony, G., & Walshaw, M. (2007). *Effective pedagogy in pāngarau/mathematics: Best evidence synthesis iteration (BES)*. http://www.educationcounts.govt.nz/publications/series/2515/5951

Barasa, L. (2020). Teacher quality and mathematics performance in primary schools in Kenya, *African Journal of Research in Mathematics, Science and Technology Education, 24* (1), 53-64, https://doi.org/10.1080/18117295.2020.1734164

Baroody, A. J., & Purpura, D. J. (2017). Early number and operations: Whole numbers. In J. Cai (Ed.) *Compendium for research in mathematics education*, 308-354. Reston, VA: National Council of Teachers of Mathematics.

Bethall, G. (2016). *Mathematics education in Sub-saharan Africa: Status, challenges, and opportunities.* Cambridge Education, End Poverty, World Bank. https://www.camb-ed.com/intdev/article/224/mathematics-education-in-sub-saharan-africa

Bold, T., Filmer, D., Martin, G., Molina, E., Stacy, B., Rockmore, C., Svensson, J. & Wane, W. (2017). Enrolment without learning: Teacher effort, knowledge, and skill in primary schools in Africa. *Journal of Economic Perspectives, 31*(4), 185-204. https://doi.org/10.1257/jep.31.4.185

Bray, A., & Tangney, B. (2017). Technology usage in mathematics education research–A systematic review of recent trends. *Computers & Education*, *114*, 255-273. https://doi.org/10.1016/j.compedu.2017.07.004

Chauhan, S. (2017). A meta-analysis of the impact of technology on learning effectiveness of elementary students. *Computers & Education*, 105, 14-30. https://doi.org/10.1016/j.compedu.2016.11.005

Cheung, A. C. K., & Slavin, R. E. (2013). The effectiveness of educational technology applications on mathematics achievement in K-12 classrooms: A meta-analysis. *Educational Research Review*, *9*(1), 88-113. http://dx.doi.org/10.1016/j.edurev.2013.01.001

Clements, D. H., Fuson, K. C., & Sarama, J. (2017). The research-based balance in early childhood mathematics: A response to Common Core criticisms. *Early Childhood Research Quarterly*, *40*, 150-162. https://doi.org/10.1016/j.ecresq.2017.03.005

Codding, R. S., Mercer, S., Connell, J., Fiorello, C., & Kleinert, W. (2016). Mapping the relationships among basic facts, concepts and application, and Common Core curriculum-based mathematics measures. *School Psychology Review*, *45*(1), 19-38. https://doi.org/10.17105/SPR45-1.19-38

Crook, S., Sharma, M., & Wilson, R. (2017). Teachers' transition into 1:1 laptop environment: A longitudinal case study of four science teachers over 5 years. *International Journal of Innovation in Science and Mathematics Education*, *25*(5), 38-56.

Deunk, M. I., Smale-Jacobse, A. E., de Boer, H., Doolaard, S., & Bosker, R. J. (2018). Effective differentiation practices: A systematic review and meta-analysis of studies on the cognitive effects of differentiation practices in primary education. *Educational Research Review*, *24*, 31-54.

Dickerson, A., McIntosh, S., & Valente, C. (2015). Do the maths: An analysis of the gender gap in mathematics in Africa. *Economics of Education Review*, *46*, 1–22. https://doi.org/10.1016/j.econedurev.2015.02.005

Fuson, K. C., Kalchman, M., & Bransford, J. D. (2005). Mathematical understanding: An introduction. In M. S. Donovan, & J. Bransford (Eds.), *How students learn: Mathematics in the classroom* (pp. 217-256). https://www.nap.edu/read/1110

Grimalt-Álvaroa, C., Ametllerb, J., & Pintóa, R. (2019). Factors shaping the uptake of ICT in science classrooms. A study of a large-scale introduction of interactive whiteboards and computers. *International Journal of Innovation in Science and Mathematics Education, 27*(1), 18-36. http://dx.doi.org/10.30722/IJISME.27.01.002

Hanushek, E. A., Schwerdt, G., Wiederhold, S., & Woessmann, L. (2015). Returns to skills around the world: Evidence from PIAAC. *European Economic Review*, 73, 103–130. https://doi.org/10.1016/j.euroecorev.2014.10.006

Hattie, J. (2017). *Visible learning for mathematics, grades K-12: What works best to optimize student learning.* Thousand Oaks, CA: Corwin US.

Heatly, M. C., Bachman, H. J., & Votruba-Drzal, E. (2015). Developmental patterns in the associations between instructional practices and children's math trajectories in elementary school. *Journal of Applied Developmental Psychology*, *41*, 46-59. https://doi.org/10.1016/j.appdev.2015.06.002

Higgins, K., Huscroft-D'Angelo, J., & Crawford, L. (2019). Effects of technology in mathematics on achievement, motivation, and attitude: A meta-analysis. *Journal of Educational Computing Research*, 57, 283-319. https://doi.org/10.1177/0735633117748416

Information and Communication Technology (ICT) Authority, Republic of Kenya. (2016, October 20). *Government starts distribution of Digischool devices to over 22,000 public primary schools [Press release]*. http://icta.go.ke/2016/10/20/government-starts-distribution-of-1-2-digischool-devices-to-over-22-000-public-primary-schools/

IST-Africa Consortium (2018). *Report on ICT Initiatives and Research and Innovation Priorities*. http://www.ist-africa.org/home/files/IST-Africa_D2.1_ICTInitiatives_ResearchInnovationPriorities_v2_Dec18.pdf

Kenya National Examinations Council (KNEC) (2020). Monitoring learner achievement at class 3 level of primary school education in Kenya. https://knec.ac.ke/wp-content/uploads/2020/09/NASMLA-Class-3-Final-Report-18.08.2020.pdf

Kim, Y.-S. G., Boyle, H. N., Zuilkowski, S. S., & Nakamura, P. (2016). *Landscape report on early grade literacy*. https://allchildrenreading.org/wordpress/wp-content/uploads/2017/12/USAID-Landscape-Report-on-Early-Grade-Literacy.pdf

Kisirkoi, F. & Kamanga, A. N. (2018). Continuous teacher professional support for effective implementation of basic education curriculum framework. *Education Quarterly Reviews*, *1*(2), 309-317. http://dx.doi.org/10.31014/aior.1993.01.01.31

Li, Q., & Ma, X. (2010). A meta-analysis of the effects of computer technology on school students' mathematics learning. *Educational Psychology Review, 22*, 215-243. http://dx.doi.org/10.1007/s10648-010- 9125-8

Lysenko, L., Rosenfield, S., Dedic, H., Savard, A., Idan, E., Abrami, P.C., Wade, C. A., & Naffi, N. (2016). Using interactive software to teach foundational mathematical skills. *Journal of Information Technology Education: Innovations in Practice. 15*, 19-34. http://www.jite.org/documents/Vol15/JITEv15IIPp019-034Lysenko2154.pdf

Mayer, R. E. (2008). Applying the science of learning: Evidence-based principles for the design of multimedia instruction. *American Psychologist*, *63*, 760-769. http://dx.doi.org/10.1037/0003-066X.63.8.760

Ministry of Education (MoE), Republic of Kenya.(2016). *Mathematics' Teacher Guide. Grade 1*.

Ministry of Education (MoE), Republic of Kenya. (2018, April). *Kenya GPE Primary Education Development project (PRIEDE). Early Grade Mathematics. Teachers' training manual.* https://www.education.go.ke/images/GPE_PRIEDE/EGM-Training-manual-2018.pdf

Momanyi, J. M., & Rop, P. K. (2020). Teacher preparedness for the implementation of competency-based curriculum in Kenya: A survey of early grade primary school teachers' in Bomet East Sub-County. *The Cradle of Knowledge: African Journal of Educational and Social Science Research*, *7*(1), 10-15. https://serek.or.ke/conferencejournals/index.php/AJESSR/article/download/44/24

National Council of Teachers of Mathematics (NCTM). (2014). *Principles to actions: Ensuring mathematical success for all*. Reston, VA: NCTM.

National Research Council. (2011). Successful K-12 STEM education: Identifying effective approaches in Science, Technology, Engineering, and Mathematics. Washington, DC: The National Academies Press. https://nap.nationalacademies.org/catalog/13158/successful-k-12-stem-education-identifying-effective-approaches-in-science

Ngware, M.W., Ciera, J., Musyoka, P.K. & Oketch, M. (2015). Quality of teaching mathematics and learning achievement gains: evidence from primary schools in Kenya. *Educational Studies in Mathematics. 89,* 111–131. https://doi.org/10.1007/s10649-015-9594-2

Pitchford, N. J., Chigeda, A., & Hubber, P. J. (2019). Interactive apps prevent gender discrepancies in early-grade mathematics in a low-income country in sub-Saharan Africa. *Developmental Science*. *22*(5), https://doi.org/10.1111/desc.12864

Platas, l. M., Ketterlin-Geller, l.R., & Sitabkhan, Y. (2016). Using an assessment of early mathematical knowledge and skills to inform policy and practice: Examples from the early grade Mathematics assessment. *International Journal of Education in Mathematics, Science and Technology*. *4*, 163-173. https://doi.org/0.18404/ijemst.20881

Ran, H., Kasli, M., & Secada, W. G. (2021). A Meta-analysis on computer technology intervention effects on mathematics achievement for low-performing students in K-12 classrooms. *Journal of Educational Computing Research. 59.* 119-153. https://doi.org/10.1177/0735633120952063

Rawal, S., Aslam, M. & Outhred, R. (2019). GPE 2020: *Country-level Prospective Evaluations. Global Partnership for Education first annual report. Kenya*. Retrieved from https://www.globalpartnership.org/content/gpe-2020-country-level-prospective-evaluations-kenya

Stanovich, K. E. (2009). Matthew effects in reading: Some consequences of individual differences in the acquisition of literacy. *Journal of Education, 189*(1–2), 23–55. https://doi.org/10.1177/0022057409189001-204

Tikly, L., Joubert, M., Barrett, A.M., Bainton, D., Cameron, L., & Doyle, H. (2018). *Supporting secondary school STEM education for sustainable development in Africa*. Bristol Working Papers in Education. Working Paper# 05/2018. http://www.btistol.ac.uk

Williams, K. T. (2004). *Group Mathematics Assessment and Diagnostic Evaluation (G•MADE).* Circle Pines, MN: AGS Publishing.

World Bank. (2018). *World development report 2018: Learning to realize education's promise.* http://www.worldbank.org/en/publication/wdr2018

UNESCO. Mahatma Gandhi Institute of Education for Peace and Sustainable Development. (2019). *Rethinking pedagogy: exploring the potential of digital technology in achieving quality education.* https://unesdoc.unesco.org/ark:/48223/pf0000372786.locale=fr

Uwezo. (2016): Are Our Children Learning? Uwezo Kenya Sixth Learning Assessment Report. http://www.uwezo.net/wp-content/uploads/2016/12/UwezoKenya2015ALAReport-FINAL-EN-web.pdf