Title:

Can a game application that boosts phonics knowledge in kindergarten advance 1st grade reading?

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Abstract

The Kalulu software is a tablet-based suite of phonics and reading-related lessons and minigames. In a previous intervention with a previous version of the software in 1st grade students, fluency and comprehension were boosted, but only when used in concert with reading instruction at the start of the year. Here, we asked whether a similar intervention would be more efficient if it started a year earlier, in kindergarten. Forty classes (1092= children) were randomized into playing Kalulu phonics or an active matched control game (Kalulu numbers) for the first half of the year. Those assignments were reversed in the second half of the year. Ten non-randomized business-as-usual classes also participated. In a cross-over effect, children who used the phonics version improved in letter naming, grapheme-phoneme matching and reading fluency, while those with the number version improved in number knowledge. In a longitudinal follow-up, intervention participants maintained an advantage in phoneme awareness and grapheme-phoneme matching at the start of 1st grade, but this advantage failed to translate into school literacy gains in the middle of 1st grade, and no longitudinal benefits were found for numbers. Those results improve our understanding of when and for how long to introduce phonics and question the possibility that a short-term intervention may address the complex challenges of long-term educational goals.

Introduction

As one of the few examples of successful applications of cognitive science to classrooms, phonics instruction has emerged from the “reading wars” as the clear winner in producing the largest literacy gains for all children (Castles et al., 2018). This finding is supported by randomized control trials and longitudinal follow-up assessments (for national reports including meta-analyses, see National Reading Panel, 2000 from the United States of America and Rose, 2006 from Great Britain). It converges with functional brain imaging studies which show how a standard reading circuit that involves both grapheme and phoneme processing nodes gets established early on during reading acquisition, and can be particularly boosted by phonics instruction (e.g. Brem et al., 2010; Dehaene et al., 2015; Maurer et al., 2010; Turkeltaub et al., 2003). Studies comparing children before and after they learn to read highlight an activation in a part of the left occipito-temporal pathway dedicated to visual recognition that becomes sensitive to letter strings and develops increasingly efficient connections to regions specialized in processing speech sounds such as the planum temporale (Dehaene et al., 2015; Dehaene-Lambertz et al., 2018a; Monzalvo & Dehaene-Lambertz, 2013a).

Today, the results of this collaboration between science and education have come full circle, as phonics becomes more and more prevalent in literacy curriculum. Phonics mastery has become central to standardized testing in several different countries (e.g., the Common Core evaluations in the United States; the Phonics Check in the United Kingdom; the EvalAide program in France). The question now is not so much if or why this method works, but what are the best practices for success. Several tenets have emerged. First, cracking the alphabetic code, a complex cultural invention, is a difficult task for children, meaning that the grapheme-phoneme correspondences of a language should be explicitly taught. Preliterate children exposed to print, but merely instructed to recognize words such as *fat* and *bat* fail to transfer their learning when shown a new word such as *fun* and asked if the word is “fun” or “bun” (Byrne, 1992). In other words, they do not implicitly learn letter-sound combinations and transfer them to new stimuli. Second, explicit phonics instruction should also follow a systematic progression (Graaff et al., 2009), in which grapheme-phoneme correspondences are introduced in a rational order taking into account their frequency and consistency in a given orthography (Ehri et al., 2001). These two findings have been central to developing a

phonics curriculum, but many other procedural questions remain, such as when to start, with which types of activities, for how long, etc.

Numeric responses to literacy curriculum

With the advent of technology to provide on-line classes and individualized learning through adaptive software, teachers and parents are also searching for numeric options to support traditional classroom literacy curriculum. Technology has been important in improving our lives and how we work, but there is no evidence that its increased use in the classroom translates into greater educational gains (OECD, 2015). In fact, there is considerable evidence that the human brain is highly attuned to linguistic and social interactions, and often learns most optimally from another human being (Csibra & Gergely, 2009; Dehaene, 2020). Nevertheless, evidence suggests that technology may usefully complement classroom learning practices, when the learning software is developed using principles from the cognitive sciences (Hirsh-Pasek et al., 2015) and when its efficacy is verified through randomized control trials. In fact, phonics instruction appears to be one area where children are easily aided by learning software, since games can introduce many grapheme-phoneme correspondences requiring active ‘drill-and-practice’ to automatize their assimilation. A successful example is the computer-based phonics method Graphogame (www.graphogame.com) (Ojanen et al., 2015; Richardson & Lyytinen, 2014). Research has shown that playing Graphogame leads to behavioral improvements as well as to an increased activation of the left occipito-temporal visual word-form system, a marker of sensitivity to print in the brain, after only a few weeks of use (Brem et al., 2010).

In our own research in France, a randomized control study comparing the phonics software ELAN to a math control game was successful in supporting literacy gains (Potier Watkins et al., 2020). The tablet-based game ELAN was specifically built for explicit systematic phonics instruction in 1st grade. Students randomized to using ELAN in the first half of first grade showed significant improvements in decoding and reading comprehension skills. The decoding task evaluated the average number of words and pseudowords that could be read in one minute, while the comprehension task required correctly choosing a picture that best described a short written sentence, amongst distractor pictures that were either syntactic or semantically altered. Importantly, significant gains were only achieved by children that participated in the reading intervention during the first half of the year, coinciding with the

time point when children were first receiving phonics instruction in the class. In France, 1st grade is the first year of formal literacy training. Using the application during the second half of the year, as a review or as an aid to struggling readers, failed to produce significant improvements. Additionally, children that used the reading intervention at the beginning of the year continued to make significantly more correct responses at the end of the year.

Our finding of improved reading comprehension supported the hypothesis that the automatization of decoding skills can free up cognitive resources for comprehension. It fits with the Simple View of Reading, which states that written comprehension is the product of decoding and spoken language comprehension (Hoover & Gough, 1990). But perhaps even more importantly for the goal of better understanding ‘what works’, the aforementioned results highlight a very specific and early window for phonics use. While our initial hypothesis was that phonics practice should always improve automatization and reading, no matter if used during the initial learning phase of school year or as review in the second half of the year, this was not the case. This finding is also supported by other recent reports that phonics instruction is critical in the early stages of learning. In one intervention study, classrooms that taught many grapheme-phoneme correspondences early in learning (i.e. up to two a week, compared to the frequent practice of once a week) produced greater literacy outcomes (Sunde et al., 2020). In France, an observational study of 1st grade teaching practices and student outcomes also demonstrated improved reading ability in classes where a larger number of grapheme–phoneme correspondences are taught early in the year (Goigoux, 2017). Critically, the National Reading Panel meta-analysis (National Reading Panel, 2000) reported a larger effect size when phonics instruction began early ($d = 0.55$), compared to after 1st grade ($d = 0.27$).

The ELAN intervention (Potier Watkins et al., 2020) provided children with the ability to learn new grapheme-phoneme correspondences at their own pace. During a pilot study, it was observed that children completed a single lesson in 25 minutes on average. Using the software in the classroom for 20-minutes three times a week meant that children could easily practice two new correspondences a week. However, there were two major limitations to clearly understanding if the early practice of many grapheme-phoneme correspondences was critical to our results. Our software taught children letter-sound relationships in a programmed order, without taking shortcuts to adapt to the student’s level. Undoubtedly, students from the 2nd-half of the year did move through the levels quicker, and the game did

adapt to their skills by requiring faster answers, with the goal of building automatization, but the experience was still one of review. If the game could have assessed and provided tailored practice of grapheme-phoneme correspondences that had not been mastered, then our results may have been different. The second limitation to the study was one common to educational research: our intervention provided an extra experience to literacy education in the class, while the latter remained uncontrolled. The ELAN suite was designed to complement many of the most common manuals used in reading education, but it could have been more complementary to certain methods than others.

In the present project, we aimed to address these two limitations and to obtain new data capable of improving our knowledge of the optimal time window for phonics intervention. We decided to retest the pedagogical principles of explicit systematic software-assisted phonics training, but to do so in kindergarten classrooms, one year before formal reading instruction begins in the French school system. Our logic was that an intervention at that age would provide a better controlled, standardized amount of phonics teaching, well adapted to the children's current instruction level, and would determine if such an approach can yield long term benefits.

In French kindergarten, the national program specifies a compulsory teaching of language development, oral comprehension, phoneme awareness (through oral manipulation) and writing. Children are expected to apprehend the "alphabetic principle" — understanding that there are predictable relationships between sounds and letters. However, the focus of letter-sound relationship training, according to the official program, is geared towards the mere recognition of the printed word as representing sounds, as well as early attempts at writing. In fact, it states that "there is no pre-reading in Kindergarten" (*Programme d'enseignement de l'école maternelle*, 2015). Our first concern was that the absence of reading instruction may be because children are considered developmentally too young. This concern was assuaged by previous research showing benefits of pre-1st grade phonics programs. It has been demonstrated that children can learn letter-sound relationships as early as preschool (Wolf, 2016), that mentoring kindergarten teachers in phonics teaching techniques improves reading skills at the end of kindergarten and in 1st grade (Ehri & Flugman, 2018), and that early phonics and small group reading interventions provide the biggest effect sizes for kindergarteners at-risk for reading difficulties (for a meta-analysis, see Cavanaugh et al., 2004). Computer-based programs for reading acquisition have also shown benefits in

kindergarten literacy programs (Comaskey et al., 2009; de Graaff et al., 2009). Taken together, testing our phonics software seemed relevant and not completely incongruent with the current kindergarten learning goals. Furthermore, any positive impact of the software on reading would occur in the absence of formal reading instruction in the class.

Our software: Kalulu phonics

Based on teacher recommendations from the ELAN project as well as pilot sessions with a kindergarten class, we made several principled adjustments and rebranded the game under the name “Kalulu” (a clever rabbit character in Swahili folklore). Adjustments included reducing the level of difficulty in several word encoding games and removing the need to pass a lexical decision task, which was required in ELAN for passage from one level to the next. Pilot studies showed that while children were easily able to understand and play games of reading syllables and word-building, the double-task of decoding a word and deciding if it was a real word or a made-up word proved confusing and frustrating. The lexical decision minigame was kept as a measure of reading progress, but not as a test to pass a level.

Like its predecessor, Kalulu phonics teaches children the grapheme-phoneme correspondences in an order that takes into account their frequency and consistency in written language. This progression was determined using an automatized neural-network based approach that we developed to automatically detect the grapheme-phoneme correspondences (GPC) then calculate their frequency and consistency in any language (Potier Watkins et al., 2019). We used the Manulex children’s print database to train our model (Lété et al., 2004). The lesson progression is provided in the supporting materials and downloadable on the project website www.ludoeducation.fr. Several adjustments were made to the ordering of the lessons in concordance with other existing French phonics manuals familiar to teachers (e.g., teaching all the primary vowel sounds in the beginning, introducing fricative consonants, before occlusive ones). Each grapheme-phoneme lesson was introduced in three steps commonly used by teachers or supported by research as benefitting phoneme processing and grapheme memorization (Fig. 1a). In step 1, clicking on the grapheme starts a video of an older child pronouncing the corresponding phoneme, with a zoom on the child’s mouth and explicit articulation to enhance auditory signal-to-noise and focus attention on the articulatory gestures underlying each phoneme, an early aid in reading acquisition (Boyer & Ehri, 2011; Castiglioni-Spalten & Ehri, 2003). In step 2, clicking on the grapheme produces a

voice emphasizing the phoneme sound and its presence at the onset of the name of a picture (e.g., 'aaa, aaapple') to facilitate memorization of the sound by linking it to a known word. In step 3, the child traces the grapheme in both upper and lower case on the touch screen. Previous research has made the hypothesis that haptic exercises with letters, such as learning to write or to trace letters with the finger improve reading skills because they provide an additional motor code to support memory for grapheme shape (Bara et al., 2004; Bara & Gentaz, 2011). Children can repeat these steps as much as needed.

After completing the lesson, three games are proposed to automatize recognition of the grapheme-phoneme correspondence (Fig.1, b-d). The minigames in Kalulu all have the goal of spurring the child to make faster and faster responses and automatize the recently acquired grapheme-phoneme relationships with gradual difficulty. The simplest games develop phonics awareness through syllables. Children hear the grapheme-phoneme correspondence in a syllable, either as a single vowel, consonant-vowel or vowel-consonant, and must click on the corresponding written stimulus on screen. Once children have learned enough grapheme-phoneme pairs to build short words, they practice their knowledge in reading and spelling games. Another game was specifically designed to develop knowledge of French morphology by highlighting the silent letters that mark gender and plurals in words. Difficulty is created by varying the distractors and the rate of targets and distractors. All syllables and words presented in Kalulu are 100% decodable from the lessons learned.

Figure 1

The game algorithm aims to provide appropriate distractors to each target. Only previously learned grapheme-phoneme correspondences can act as distractors (only learned material is presented in the minigames). Furthermore, only vowels are presented as vowel distractors and consonants as consonant distractors. Distractors in a minigame are chosen from a visual similarity matrix adapted from another study of similarity judgments of letter pairs (Boles & Clifford, 1989). Initial items are chosen (when possible) to be >0.75 in similarity to the target (1 being the matrix diagonal, and 0 being maximally different items). If the player makes a mistake in the minigame, then the corresponding threshold on distractor similarity is lowered. The game also builds an internal model of the child's confusion between targets and distractors, by keeping constant track of performance for each GPC and amount of confusion

with other graphemes phonemes. Across games, the player is required to maintain a >75% score for all GPC. If the child makes too many mistakes across several games, and its score dips below the 75% threshold, then the corresponding grapheme is reintroduced as a target. Along with adapting the presented stimuli, each of the minigames also has several levels of difficulty that lead to changes in the number of distractors presented and response time requirements. These levels increase or decrease in difficulty for every two identical minigames won or lost in a row.

A matched active control: Kalulu numbers

A criticism of our previous study was that our control software for enhancing number knowledge, Number Catcher, was not directly matched to the phonics games and did not produce any benefits on our control measures for early math ability. Participating teachers also remarked that the children's interest in the control game dissipated quickly as it was always the same (whereas the minigames for reading constantly changed). For the current project, our goal was to use a better matched control. To do this, we adapted the minigames from our Kalulu phonics program into number games that followed similar visuals, rules and procedures to make them comparably challenging and engaging (Figure 2). The need for a close match between the phonics and number game implied that we could not include all of the principles that are known to facilitate the acquisition of numeracy, as previously implemented for instance in the NumberRace software (Räsänen et al., 2009; Wilson et al., 2006). Rather, for close similarity to the phonics program, we developed our games to build associations between symbol and meaning. In the case of numbers, this meant learning to associate symbolic numbers (either number names, e.g. 'two', or indo-arabic numerals, e.g. '2') to the corresponding quantity (**').

Kalulu numbers teaches numbers 0-100 in forty lessons (see annex for the game progression). Each lesson starts with a 3-part sequence to associate number with meaning using techniques supported by the literature (Figure 2a). First the number is presented in its counting sequence on a 10x10 game board. Playing on game boards that demonstrate the linear structure of numbers has been linked with improved numeracy (Laski & Siegler, 2014; Siegler & Ramani, 2009). Next, the child is introduced to different quantity representations of the number. This is a common practice shown to improve math readiness in school (Skwarchuk et al., 2014). Finally, children are asked to trace the number symbol twice to help

memorize its form. The hypothesis with letters is that haptic exercises like tracing or writing may provide an extra motor code and reduce instances of mirror-writing (Gottfried et al., 2003). Mirror writing is also a phenomenon that exists in numeral writing (Arnas et al., 2004; Fischer, 2011), and we reasoned that this practice could help cement the memory for numerals.

Once the learning session is complete, as with the reading path, several minigames are proposed to cement comprehension (Figure 3, b-f). The first type of minigame focuses on automatizing fluency of association between number name, number symbol and quantity. Once children learn enough numbers, a counting game is introduced. The counting game requires helping a game character find the correct number in a counting series starting from either '0' or another random number and ending at specific number (e.g., "starting from the number 5, count all the numbers up to the number 8"). Once children learn numbers above 10, a game is introduced to associate numerals to quantities, taking into account place value (e.g., if asked to find the number matching the quantity of '28', first the child would match the symbolic number '20', then the symbolic number '8'). Finally, we introduce arithmetic games for small additions (<10). Passage from one garden to the next is tested by a 'choose the biggest number task', where children have 3 minutes to choose the biggest between two numbers, with 20 pairs presented in total.

Figure 2

An encompassing experiment and control environment

Both the experimental phonics pedagogy and the active control game were presented in the same game environment (Figure 3). A game panel allowed teachers to select Kalulu phonics or numbers. In both pedagogical goals, the game is introduced by the mascot Kalulu, a rabbit that explains that learning is like cultivating the garden of the mind: the more you learn, the more vibrant your garden will grow. The main screen of the game represents a brain in a schematic format of 20 gardens. The player touches the highlighted garden to zoom-in. Across all gardens runs a letter path and a number path. Nodes along the path each represent a lesson for learning a new grapheme-phoneme relationship (letter path) or a new number (number path). Pressing the node opens a lesson followed by three minigames to practice the lesson learned. Once the minigames have been won, at a minimum score of 80% correct, the next

node on the path opens. With each lesson learned and game won, the once barren garden flowers with plants. Game play and rules are identical on the two paths. Kalulu was developed using the open-source platform Godot to ultimately allow non-licensed distribution of the game, and is currently available in compiled form at www.ludoeducation.fr.

Figure 3

Experimental study

In summary, the main goal of the project was to test the Kalulu phonics software with Kindergarten children to see if teaching many grapheme-phoneme correspondences at this early age could boost phonics knowledge in kindergarten and literacy in 1st grade. The Kalulu software was adapted from our ELAN software and piloted for conformity to Kindergarten usability as a stand-alone game needing minimal explanation from the teacher. Pilots were conducted for several months in a classroom with a member of the lab observing interactions and reporting to the developer. Using a cross-over design, we tested the game with kindergarten classes, comparing the phonics software to both an active control (classrooms with the Kalulu math software) and a passive control (classes without tablets). To assess possible long-term benefits, we also followed-up on participants during the subsequent year (1st grade), using the results on national standardized tests, up to a year after exposure to the intervention.

Methods

Participants

Two different school districts in France participated in the project (Nice and Poitiers). Each district recruited twenty classes to participate in a tablet-based intervention, as well as five classes for a tablet-free “business-as-usual” control group. Participation in the study was proposed to teachers by the school district and on a voluntary basis. At the beginning of the year, teachers sent home with students a letter from the lab explaining the project, accompanied with an ‘opposition form’. Parents could return the form if they wished to opt-out. At the start of the school year, 1092 students were initially counted in the intervention. The project was approved by the ethical committee CERES (Conseil d’évaluation éthique pour les recherches en santé) on 25/04/2017.

Design

The school districts required that all children eventually have access to both of the intervention games. Thus, we employed a 2-period crossover design (similar to Potier Watkins et al., 2020). All children in the study were tested at the beginning of the year (labeled pretest), after which each of the 40 intervention classes was randomly assigned to either playing with the Kalulu phonics game for the first half of the year, then the Kalulu number game for the second half (group labeled “read/math”, N = 411 children), or vice versa (group labeled “math/read”, N = 449 children). Randomization required an equal number of classes in each group and was stratified by the school district (Poitiers or Nice) and the size of the class, which varied from 5 to 28 children. Generally, a smaller class size indicates that it is a class split into two grade levels. For example, a class may have students from middle-preschool and Kindergarten. We also tested 10 ‘business-as-usual’ control classrooms (group labeled “control”; N = 232 children). These classes could not be randomized, as the teachers were interested in participating, but did not want to receive tablets. The inclusion of both an active and passive control allowed us to measure progress due to the pedagogy separate from the effect of merely introducing a tablet intervention to the class. To measure the evolution of learning, children were tested during a 3-week period before switching games (labeled midtest) and during another 3-week period at the end of the year (labeled endtest). To assess long-term benefits to using the software, children’s results on national evaluations given at the beginning and middle of the 1st grade were also examined in a longitudinal follow-up. Figure 4 provides a calendar of intervention and test sessions.

Figure 4

Procedure

Five to eight tablets (depending on class size) were sent to classes at the start of the school year. A lab member contacted each teacher individually to explain the design of the project and introduce the teacher to the project website with supporting information. Teachers were encouraged throughout the year to call or email the designated lab member with their implementation questions. This person was not aware of students’ results on the tests. Within each class, a workspace dedicated to tablet sessions was set up in a quiet space. Teachers were asked to organize small groups of students, according to the number of tablets received,

that would take turns participating in the intervention session. We also asked that groups be heterogenous in terms of their expected ability by teachers. The goal was for children to help each other and minimize the need for teacher assistance. Teachers in our previous research had reported appreciating the small group play sessions, while teachers in the current project informed us that rotating small groups between activity stations is a common practice in kindergarten and easy to implement. Research has shown that small group learning is especially beneficial for young children (for a meta-analysis see, Hattie, 2010). We would also like to mention here that small groups rotating at a tablet workstation is far more economical for large-scale implementation than having one tablet per child. Visits to the class confirmed our hope that children would help each other with the games.

Each intervention session lasted ten weeks. Teachers were asked to ensure that students play for one hour a week for at least eight weeks of the intervention period. Teachers could organize tablet time into three 20-minute sessions or two 30-minute sessions per week. This flexibility was to take into account absenteeism and time dedicated to class trips or other projects. Each of the test periods lasted three weeks.

Once the pretests were completed, teachers were informed of their intervention group (read/math or math/read). They also received an instruction book (on paper and pdf) detailing the cognitive science behind the pedagogy for their immediate group (phonics or numbers). Before starting the intervention, classes had a 2-week fall break, during which time teachers could familiarize themselves with the booklet and game. Everyone was encouraged to understand the materials in order to support children's learning in the class. However, teachers were under no obligation to modify their own pedagogy in consequence. Communications between the lab and the classes were maintained throughout the year and teachers, as much as possible, uploaded data from the tablets to the lab. In many cases, the Kindergarten classes did not have WIFI, and two classes did not enter the correct class id in their tablet. In these cases, data was sent when possible or the lab was kept abreast of progress through phone calls. Teachers were asked to report bugs and criticism of the games throughout the year. Everyone reported positive remarks and high engagement from the class. Only one child in the intervention refused to play half-way through the year. All of the classes remained in the project throughout the intervention year.

Test measures

Our goal was to see if the intervention could boost kindergarten phonics and number knowledge and improve 1st grade formal learning. To assess this question, we decided to use the national standardized evaluation given to all children at the beginning of their 1st grade year, and which assesses several aspects of the expected knowledge and predictors for reading and math achievement. By using this test during the intervention, we could measure progress through the kindergarten year and follow-up on progress on comparative measures when our participants took the national evaluations at the beginning and middle of 1st grade.

The French national evaluation program, called EvalAide (Groupe de travail du Csen, 2019), is generally administered by the teacher and done using pencil and paper, but there also exists a tablet version. Testing at all three periods during the kindergarten intervention was done on tablet by employees of each school district specialized in pedagogical teacher support. Testers attended an on-line training day to learn how to conduct the tests. Children did the test individually, wearing headphones and providing answers on their own on the touch screen. The testing administrator was present to repeat instructions if needed and ensure that all children did the test on their own. Data from the tests was subsequently sent to the lab.

The tablet version of the national evaluation for 1st grade is separated into three subtests, two testing language and pre-reading skills (FR1 and FR2) and one testing number and math skills (MA1). Due to time constraints, only a selection of questions was used. At the pretest, to assess differences in baseline knowledge, children's responses were collected on the visual attention, vocabulary and syllable awareness tasks in the FR1 subtest. At pretest, midtest and endtest children answered all the questions in the FR2 (excluding an orally presented text and comprehension task, due to errors in the recordings) and the MA1 subtest (excluding a number comparison task that did not accurately record response time). Each subtest was done in its entirety with a break between the two.

The FR2 subtest measures the abilities that have been shown to be the most predictive of reading outcomes such as oral sentence comprehension, phoneme awareness and letter name knowledge (Sprenger-Charolles et al., 2005). It also looks at phonics knowledge in a grapheme-phoneme matching task. This task is directly taught in Kalulu and is considered the backbone to reading. Grapheme-phoneme correspondences are not required teaching in kindergarten, and children are not expected to have acquired this knowledge before 1st grade.

All questions included a trial with feedback. The percentage correct for each question was collected. As we were also interested in learning if the phonics games in Kalulu could spur literacy before formal instruction, we added a 1-minute word and pseudoword reading task. This test was done on an individual basis by the tester with the child. Children had 1-minute to read as many words and then matched pseudowords as possible. We looked at the average number of words and pseudowords in a minute as a measure of reading fluency.

The MA2 subtest assesses number understanding, predictive measures of math ability and early problem-solving skills. Only numbers up to ten were shown or required as answers, ten being the highest number of focus in French kindergarten. A trial item with feedback was provided for each question. The number understanding portion of the test required associating symbolic-numbers to number-name (e.g., “Find the number ‘five’ six symbolic-numbers presented) and symbolic-number to quantity (e.g., “Touch the number that corresponds to the quantity of eggs in a basket”). Math problem solving is assessed using simple everyday word problems (i.e., “Five kids need a pen. There are three pens in the box. How many more pens do they need?”). For each question an image demonstrating the two given quantities of the problem (e.g., In the given example, an image of five kids and three pens) was provided to help the child find the solution. The predictive measures included a number-line and number comparison task. In the number-line task, children were shown a number-line from 0 to 10 with a tick mark crossing the line. Children had to choose from six options the number indicated by the tick mark. An additional number comparison task was attempted, but the results was not included in our analyses due to a design issue that prohibited us from calculating the number of correct responses made in a minute time constraint, the typical measure of analysis for this task.

For the longitudinal follow-up in 1st grade, we were authorized to access the anonymized data for participants from the national standardized tests. These tests were administered by teachers simultaneously to the entire class, with children writing their responses with pen-on-paper, except for several questions that required reading aloud individually to the teacher. Teachers uploaded students’ responses on a dedicated platform managed by the *Department of evaluation, prospective and performance (DEPP)* of the ministry of education. The test was given in the beginning of the 1st grade (September) and in the middle of the school year (January). Questions for these two periods examine similar categories of pre-reading and math skills, but the mid-year test includes more difficult material

(i.e., bigger numbers, reading and spelling) to take into account expected learning progress between the two time periods. The goal of these evaluations is to measure school progress and alert teachers to each student's strengths and difficulties, by providing them with diagnostic measures which are known to be predictive of future reading and math performance. The beginning-of-the-year test provides teachers with an objective measure of the student's achievement after the summer-lag, i.e. the frequent loss of skills acquired in the preceding school year after the two summer months (Alexander et al., 2001; McCoach et al., 2006). The middle-of-the-year evaluation provides teachers with feedback on whether the students made the expected progress and help them provide targeted interventions to children in need. The appendix provides a detailed list of the questions assessed from kindergarten to 1st grade with the different time periods and administration details.

Statistical analysis for the intervention

Given our 2-period crossover design, for each task, we first analyzed responses for the randomized part of the experimental design using a mixed analysis of variance with a 2-level between-group factor (read/math versus math/read) and a 3-level within-group test period factor (pretest, midtest, endtest). We then re-ran the same analysis including the non-randomized no-tablet control (3 x 3 Anova). To factor out pre-schooling differences amongst children, we included the covariable composite z-score computed from the individual's average z-scores on the three predictive tasks at pretest (visual attention, vocabulary and syllable awareness).

In a crossover design, we expect to see a 2-step pattern of improvement: children in the read/math group should improve in the language and reading tests at mid-test relative to the math/read intervention, whereas the latter should improve on the number and math tests. During the second session of the intervention, we should see the opposite effect of learning for each group so that no difference should eventually be found on all measures at the end test (unless one period is more conducive to learning, perhaps due to greater readiness for reading). An effect of the training is therefore expressed as a significant interaction between the group and test period. Because all children are expected to learn during the year, the passive control provides us with a measure of normal progression. To correct for multiple comparisons, we used a Bonferroni correction for each comparison by dividing the threshold on Type I error rate (α) by the number k of summary measures that we

assessed, $\alpha/k = .05/5 = .01$ for the language and reading subtest, and $\alpha/k = .05/3 = .017$ for the number and math subtest. The results we report all passed this threshold.

Participant attrition and baseline characteristics

Only children that completed the three tests given during the kindergarten intervention were examined. This included 783 children (read/math= 300, math/read = 320, control = 163). To examine the baseline balance between the two intervention and control groups, we performed an overall F test or Chi-square test (see Table 1), as well as pairwise comparisons between the three groups in terms of baseline demographic variables, the three predictive variables at pretest (visual attention, vocabulary and syllable awareness) and the pretest results in each domain (see Table 1). No differences were found between groups, except for the fluency task (the average number of word and pseudowords read in a minute). Critically, two by two comparisons revealed that a difference between the two intervention groups, $F(1, 617)=03.86$, $p=.050$ was not significant at the Bonferroni corrected threshold $p_{corrected}=0.01$. The control group did however read more items at this threshold than the math/read group $F(1, 480)=10.71$, $p=.001$, but not the read/math group $F(1, 460)=3.20$, $p=.074$. These differences were mainly due to the fact that few children attempted this test. Children were required to read the first two trial syllables in order to continue, and the proportions of children who did differed across groups (read/math=25%, math/read=20%, control=29% of the participants succeeded in reading the trials). We decided to not adjust groups based on this variable as, on average, all groups read less than one item per minute.

Table 1, Baseline characteristics at pretest for children that completed the intervention.

Results

Intervention effects

Children's progress in language and reading across the three test periods is shown in Figure 6. Performance in early number understanding and manipulation is presented in Figure 7. As expected, there was a significant effect of session on all test tasks, $p < 0.001$, demonstrating learning progression through the school year. There was also a significant effect of the

composite pre-test covariate for all measures, $p < 0.001$. Over and above those expected effects, we now report for each measure the crucial group by session interactions.

We begin by looking at the language and reading results. On the two orally presented early predictive measures for reading, i.e. oral comprehension and phoneme awareness, children in both intervention groups performed equally across all three periods, $F(2, 1234)=0.24$, $p=0.788$ and $F(2, 1234)=0.79$, $p=0.455$, respectively. Including the passive control group into the analysis revealed similar results. We did not find a group by test interaction on either of the orally presented measures (oral comprehension: $F(4, 1558)=0.45$, $p=0.769$; and phoneme awareness : $F(4, 1558)=1.40$, $p=0.232$).

A different outcome appeared when we looked at tasks that required children to manipulate letter symbols and their sounds. In letter name knowledge, there was an intervention group by test interaction, $F(2, 1234)=9.22$, $p<0.001$. Post hoc analysis at each test period showed that the intervention groups started the year with similar knowledge, $F(1, 617)=2.04$, $p=0.154$. After the first training period, however, children that used the phonics suite could recognize more letters by their letter names than children that used the number suite, $F(1, 617)=10.64$, $p<0.001$. This initial advantage disappeared at the end of the year, once both groups had had training with the Kalulu phonics suite, $F(1, 617)=2.27$, $p=0.132$. Including the control group to our analyses also produced a group by session interaction, $F(4, 1558)=4.88$, $p<0.001$. Post hoc analysis at each test period confirmed that all three groups began the year on par, $F(2, 779)=1.01$, $p=0.363$. An effect of group on the midtest ($F(2, 779)=5.36$, $p=0.005$) reflected an advantage for children in the phonics intervention group compared to the math group. No difference was found between either of the intervention groups and the control (read/math vs. control, $F(1, 460)=1.77$, $p=0.184$; math/read vs. control, $F(1, 480)=1.87$, $p=0.172$). No difference in letter name knowledge was found at the end of the year, $F(2, 779)=1.95$, $p=0.143$. All effects were significant at the Bonferroni corrected threshold.

We also found a significant intervention group by session interaction for grapheme-phoneme matching, $F(2, 1234)=25.71$, $p<0.001$. Post hoc analysis at each test period showed no effect at pretest, $F(1, 617)=1.10$, $p=0.294$. Children that received the phonics intervention during the first session performed better in grapheme-phoneme matching by the mid-year test, $F(1, 617)=35.94$, $p<0.001$, an advantage that disappeared at the endtest, $F(1, 617)=2.88$, $p=0.090$. Including the passive control group again produced a group by test session

interaction, $F(4, 1558)=14.03$, $p<0.001$. All three groups started the year with similar phonics knowledge, $F(2, 779)=1.26$, $p=0.283$. An effect of group emerged at midtest, $F(2, 779)=22.12$, $p<0.001$, showing that children who had received the phonics intervention performed not only better than children who received the math intervention, but also than the passive control, $F(1, 460)=25.40$, $p<0.001$, while no difference was found between the active and passive control, $F(1, 480)=0.14$, $p=0.704$. An effect of group extended to the endtest, $F(2, 779)=7.54$, $p<0.001$.

By the end of the year, the read/math showed a marked trend to better grapheme-phoneme understanding over the control $F(1, 460)=5.88$, $p=0.016$, while the math/read group now also made significantly more correct matches than the control, $F(1, 480)=14.68$, $p<0.001$. In quantitative terms, at the end of the school year, the group that had used Kalulu phonics games in the first session, after 4 months of no longer playing, maintained an advantage of 0.18 standard deviations over the control group, while the group that had used the phonics suite in the second half of the year had a 0.32 standard deviation advantage over the control group.

On the measure of reading fluency, the average number of words and pseudowords read in a minute, we found a significant intervention group by test interaction, $F(2, 1234)=5.32$, $p=0.005$. At the start of the year, an advantage for children that would go into the read/math group was marginally significant, $F(1, 617)=3.86$, $p=0.050$. As mentioned in the section 'Base-line characteristics at pretest', this was mainly due to the fact that slightly different numbers of children attempted this test. By the middle of the year, the group that used the phonics suite read more words than the active control, $F(1, 617)=17.32$, $p<0.001$. This advantage disappeared after both groups had used the phonics suite, $F(1, 617)=0.01$, $p=0.943$. Those results were confirmed by a significant three group by test session interaction, $F(4, 1558)=4.62$, $p<0.001$. Once again, due to the percentage of students able to attempt the test, there was a significant group difference at pretest, $F(2, 779)=5.97$, $p=0.003$. Our post hoc analyses showed that the control group started with marginally but non-significantly more words read than the read/math group, $F(1, 460)=3.20$, $p=0.074$, and significantly greater early reading ability compared to the math/read group, $F(1, 480)=10.71$, $p=0.001$. By the middle of the year, a significant group effect, $F(2, 779)=11.17$, $p<0.001$, revealed that children that had used the phonics software now read more words than either the active or the passive control ($F(1, 460)=11.65$, $p<0.001$ for the latter test). Both the math/read and control group read a

similar number of words on average by the middle of the year, $F(1, 480)=0.01$, $p=0.933$. On the endtest, we did not find an effect of group, $F(2, 779)=1.44$, $p=0.238$.

Figure 6

We now present the results for the number and math knowledge tests. For the combined number knowledge portion of the test, we found a significant group by test interaction, $F(2, 1234)=8.50$, $p<0.001$. Post hoc analysis showed that both intervention groups started on equal footing at pretest, $F(1, 617)=0.40$, $p=0.529$. By the middle of the year, children that played with the number games made more correct responses when matching symbolic numbers with their names and quantities, $F(1, 617)=19.76$, $p<0.001$. This difference disappeared by the end of the year, once both groups had had experience with the number games, $F(1, 617)=0.05$, $p=0.818$. Including the control group revealed a similar group by test interaction, $F(4, 1558)=5.26$, $p<0.001$. Post hoc tests revealed no difference between groups at pretest $F(2, 779)=0.26$, $p=0.772$. At the mid-test, a significant group effect, $F(2, 779)=10.75$, $p<0.001$ highlighted a greater number understanding for children that played with the number games than the control, $F(1, 480)=10.97$, $p<0.001$. No difference was found between the read/math and control groups $F(1, 460)=0.24$, $p=0.627$. At the end test, there was a group effect, $F(2, 779)=4.15$, $p=0.016$, with both intervention groups making more correct responses than the control (read/math vs. control, $F(1, 460)=6.38$, $p=0.012$; math/read vs. control, $F(1, 480)=7.03$, $p=0.008$). In quantitative terms, at the end of the school year, the group that had used Kalulu number games in the first session, after 4 months of no longer playing, maintained an advantage of 0.18 standard deviations over the control group, while the group that had used the math suite in the second half of the year had a 0.20 standard deviation advantage over the control group.

The word problem solving and number-line tasks did not produce a group by test interaction when taking into account only the two randomized groups (word problem solving, $F(2, 1234)=2.17$, $p=0.115$; number-line, $F(2, 1234)=0.99$, $p=0.372$) or when including the passive control (word problem solving, $F(4, 1558)=1.33$, $p=0.258$; number-line, $F(4, 1558)=0.68$, $p=0.608$).

Figure 7

Longitudinal follow-up

While using the Kalulu software boosted Kindergartner's pre-reading and math skills in the trained domains, did it also boost 1st grade school readiness, leading to better early literacy and math success? To assess this, we looked at the data from the beginning and middle of 1st grade, using the national evaluations of the participants from the kindergarten intervention. Data could be obtained from 94% of the participants (read/math=270, math/read=312, control=156). Consistent with the intervention analysis, we first looked at the randomized part of the study using one-way ANOVAs to test the main effect of group (read/math or math/read), the goal being to assess if children in the 1st grade retained more or less knowledge from the reading or math software depending on the period of exposure during the intervention year. If no difference was found between the two intervention groups, we collapsed both groups and used a similar ANOVA to compare them to the non-randomized control group. We used the same predictor composite as a covariate. We report whether the results achieve significance after a Bonferroni correction, obtained by dividing the Type I error rate by the number of measures assessed. For the beginning of the year evaluation, this is $\alpha/k = .05/4 = .013$ for the reading tests and $\alpha/k = .05/4 = .013$ for the math tests; for the mid-year evaluation, this is this is $\alpha/k = .05/6 = .008$ for the reading tests and $\alpha/k = .05/5 = .01$ for the math tests. The composite predictor continued to be significant on all tasks at $p < 0.001$. Degrees of freedom were adjusted to reflect the fact that some cells had missing data for certain questions within a test. This could have been due to a child being absent for a portion of the test, or to accidental non-reporting by the teacher. Figure 8 shows the performance at the beginning and middle of the 1st grade year for each of the read/math, math/read, and control groups, respectively, for the language & reading and number & math tests.

At the beginning of 1st grade, the two intervention groups showed similar abilities in all of the pre-reading tasks: oral comprehension, $F(1, 569)=0.30$, $p=0.586$; letter-name knowledge, $F(1, 567)=0.09$, $p=0.760$; phoneme-awareness, $F(1, 572)=0.37$, $p=0.545$; and grapheme-phoneme matching, $F(1, 573)=0.14$, $p=0.710$. We therefore collapsed the randomized groups and compared them to the passive control group using the same analysis. No difference was found between the intervention and passive control on the tasks of oral comprehension, $F(1, 725)=1.05$, $p=0.305$ and letter-name knowledge, $F(1, 721)=0.00$, $p=0.965$. In the two tasks requiring phoneme manipulation, a skill directly taught by the Kalulu reading software, the intervention groups did significantly better than the control group, in spite of

the summer break: phoneme awareness, $F(1, 727)=8.25$, $p=0.004$; grapheme-phoneme matching, $F(1, 728)=7.38$, $p=0.007$. After Bonferroni correction, both effects remained significant.

Looking at the number and math questions, no difference was found between the randomized intervention groups on any of the tasks: number knowledge, $F(1, 564)=0.14$, $p=0.712$, word-problems, $F(1, 576)=0.02$, $p=0.896$, number-line, $F(1, 573)=1.25$, $p=0.264$, number comparison, $F(1, 569)=0.06$, $p=0.807$. We collapsed these two groups and compared them to the passive control group. At this time, the control group performed comparably to the intervention on tasks of number knowledge, $F(1, 718)=0.01$, $p=0.916$; word-problems, $F(1, 732)=0.55$, $p=0.460$ and number-line, $F(1, 727)=1.02$, $p=0.313$. On the number comparison task, children that received the intervention performed significantly better than the control, $F(1, 725)=4.53$, $p=0.034$, but this difference did not survive Bonferroni correction.

By the middle of 1st grade, the two intervention groups still performed equally on the reading measure of oral comprehension, $F(1, 543)=0.72$, $p=0.395$; grapheme-phoneme matching $F(1, 545)=0.01$, $p=0.934$; reading comprehension, $F(1, 556)=0.45$, $p=0.502$; spelling, $F(1, 531)=0.00$, $p=0.949$. On phoneme awareness, this time, students that had used the reading intervention early in their Kindergarten year showed a slight advantage over students that used the method during the second half, $F(1, 556)=5.60$, $p=0.018$ while an advantage in the opposite direction was found for reading speed, $F(1, 548)=5.86$, $p=0.016$. As neither of these group effects were significant after Bonferroni correction, the two intervention groups were collapsed for comparison with the passive control. After half-a-year of formal reading education, all groups performed equally well in oral comprehension, $F(1, 692)=0.11$, $p=0.735$, phoneme awareness, $F(1, 708)=0.75$, $p=0.388$, grapheme-phoneme matching, $F(1, 693)=1.63$, $p=0.202$, reading speed, $F(1, 698)=0.97$, $p=0.326$. In tasks of reading comprehension and spelling, the control group performed better than the intervention group, $F(1, 708)=5.77$, $p=0.017$ and $F(1, 676)=12.14$, $p<0.001$, respectively. After Bonferroni correction for the 6 measures, only the effect on spelling remained significant.

As for math, in the middle of 1st grade, no difference was found between the two intervention groups on number writing, $F(1, 545)=1.36$, $p=0.248$; word-problem solving, $F(1, 556)=0.42$, $p=0.517$; arithmetic, $F(1, 533)=0.23$, $p=0.635$; number-line, $F(1, 555)=0.30$, $p=0.582$; number-comparison, $F(1, 547)=0.50$, $p=0.481$. Collapsing the two intervention groups and comparing them to the control did not produce a group effect on number-writing,

$F(1, 693)=0.490$, $p=0.49$; arithmetic, $F(1, 678)=0.68$, $p=0.414$; number-line, $F(1, 706)=0.43$, $p=0.516$; number-comparison, $F(1, 694)=0.10$, $p=0.748$. Children in the control group made more correct responses than the intervention group in solving math word problems, $F(1, 708)=5.23$, $p=0.023$, but this effect was not significant after Bonferroni correction for the 5 tests.

Figure 8

Discussion

This study sought to remediate several limitations brought up in our first intervention with the ELAN software. On the one hand, during the ELAN intervention, we were concerned that our active number control provided an insufficient comparison for our reading software, since it did not produce any detectable benefits in number understanding. We therefore redesigned our software to include the active math control within the same engaging environment. In this respect, the Kalulu intervention was successful as both groups showed improved links from symbols (either graphemes or numbers) to their meaning (either phonemes or quantity) depending on whether they used the letter or number software. Compared to the ELAN intervention, the current study was adapted to Kindergarteners. Our reasoning was that, since French Kindergarteners do not receive formal reading instruction, this would allow us to measure, more directly, the benefits from using the software, without any interference from the intense literacy training that children receive in 1st grade. In this respect too, our intervention was successful. Progress was made on the questions tested, relevant to the treatment intervention and independently of whether the training took place in the first half or the second half of the year. Furthermore, both intervention groups, irrelevant of session, behaved similarly in the longitudinal follow-up.

Compared to the passive control group, using the Kalulu software provided a significant gain in symbol-to-meaning mappings, for both grapheme-phoneme and number-quantity knowledge. This benefit imparted from the software was present regardless of the timing of the training session. However, this improved understanding of the symbols and their meaning did not transfer to gains in reading or math ability, over and above the normal learning progression as exemplified by the control group. In other words, Kalulu was only successful in imparting knowledge on the learning tasks that were made explicit by the game.

Encouragingly, children that had taken part in the intervention arrived in 1st grade with an advantage in grapheme-phoneme knowledge and phoneme awareness, 4 months after the intervention. Furthermore, in spite of the fact that the intervention and testing during the intervention period had been done on tablets, students were able to transfer their knowledge to pen-and-paper tasks. This outcome was encouraging as it showed that learning by using the tablet was not just context dependent. Both phoneme awareness and letter-sound knowledge are important predictors of reading performance (Bradley & Bryant, 1983; Cunningham, 2001; Melby-Lervåg et al., 2012; Piquard-Kipffer & Sprenger-Charolles, 2013). At the beginning of 1st grade, there was also a trend to improved number comparison ability compared to the passive control. Symbolic number comparison has been previously shown to be a predictor of math performance in the early years of elementary school (Lyons et al., 2014).

In spite of these encouraging outcomes at the start of 1st grade, by the middle of the year, there was no longer any detectable advantage to having been exposed to Kalulu in kindergarten. In fact, children from the passive control did better in spelling, and showed a trend towards greater reading comprehension and word problem solving. What could have happened from the start to the middle of 1st grade is unknown to us, as we do not have access to school information, but only to the data provided by the National Evaluations. One possibility is that software training yields a long-term negative effect. In the past, methods promoting pure phonics instruction have been criticized for possibly developing an over-dependence on decoding skills while ignoring the end goal of fluent reading, i.e., word recognition. Software games may also distract children away from more classical and possibly more efficient modes of classroom learning. While a thorough rejection of those hypotheses requires further research, we find them doubtful given our earlier results that comprehension was improved when 1st grade children received a computer-based phonics intervention, with benefits lasting 4 months after the intervention (Potier Watkins et al., 2020).

Another explanation, supported by the results from our previous intervention (Potier Watkins et al., 2020), is that this project minimized the importance of introducing grapheme-phoneme correspondences simultaneously with the focused experience of learning to read in the classroom. As stated, the goal of our phonics software was to provide children with many grapheme-phoneme correspondences early in learning, a practice supported by previous observational and intervention studies (Goigoux, 2017; Sunde et al., 2020). In fact, children that participated in the intervention were exposed to more grapheme-phoneme training than

children in the control group, as shown by the end test and early 1st grade results. While we always assumed that this advantage would boost literacy learning, it may have had the adverse effect of decorrelating phonics education from classroom practices such as actual reading aloud, which are necessary for children to learn to read. In other words, our students learned about phonics, but given that our software does not include voice recognition, children could not apply this new knowledge to actual reading practice, perhaps leading to a disconnection of their abstract grapheme-phoneme knowledge from any practical application. Furthermore, 1st grade teachers were not aware that students from the intervention had already started to build their phonics knowledge, and hence could not provide adapted literacy practice. Thus, students from the intervention probably began their 1st grade year reviewing learned grapheme-phoneme correspondences, while children from the ‘business-as-usual’ control would have learned this novel information simultaneously with common classroom practices, such as reading-aloud. In this scenario, children from the control condition may have benefitted from the advantageous situation of introducing phonics in combination with structured reading practice, while the intervention students could have been demotivated by receiving a mere review of what they already knew during their first months of literacy education. Our design possibly recreated a similar situation to the one that we saw in our first experiment, whereby children that used the games as review did not benefit, only in this case the 1st grade classroom experience was the review.

A third explanation is possible: the changes seen during 1st grade may be due to the French national assessments. As described earlier, these tests are specifically designed to evaluate the pupils at the beginning of 1st grade and provide individualized feedback in a timely manner. Children from the control group began the year with significantly lower skills in phoneme awareness and grapheme-phoneme matching. It is not impossible that these students received additional targeted individualized attention in order to subvert this early deficit. The National Education system of France provides teachers with both detailed explanations of the tests and corresponding targeted remediation exercises.

Future directions

There are several positive aspects to the present study. Teachers’ reports on the Kalulu software were generally positive, and children learned, played, and enjoyed the games. Our participants made initial gains in reading readiness, and these improvements persisted after

the summer-lag, whereas a slight decline across all academic areas is generally seen in all students over the summer (Borman, Benson, & Overman, 2005; Cooper, Nye, Charlton, Lindsay, & Greathouse, 1996; Heyns, 1987; Murnane, 1975). We cannot say, however, that Kalulu training in Kindergarten reproduced the results with ELAN software in 1st grade. The present children improved in tasks of symbol to meaning understanding compared to the control group, but unlike with ELAN, this knowledge did not transfer to reading speed or comprehension improvement.

Any future direction of this project should seek to improve the disappointing follow-up results, i.e., the fact that, in spite of much previous research showing that phoneme awareness and letter-sound knowledge are predictors of reading acquisition (Cunningham, 2001), the initial boosts in phonics obtained with Kalulu did not suffice to boost literacy. There are many aspects of the Kalulu game that could be improved. One of the most glaring issues is that the game teaches reading indirectly, by clicking on letters, words or pictures, rather than directly through reading aloud. To the best of our knowledge, this is true of all similar software and is due to the unreliability of current technology in recognizing the nuances of children's vocal productions (i.e., several programs tested could not reliably detect the difference between /b/ and /d/ sounds, which is crucial to ensure that children do not make phonemic or mirror errors). Our game requires children to read in their heads and to associate an orally presented syllable or word with its written form. Some of the harder games also require encoding. For example, children hear a word, then have to break it down into its phonemes and assemble the corresponding graphemes one by one. A solution would be to integrate reliable voice-recognition or involve teachers or advanced students in reading aloud practice.

Another criticism may be that our intervention was too early, and that it would be better to introduce it in 1st grade. Not much is known about the optimal windows for reading acquisition, and we did obtain better results in a previous 1st grade intervention (Potier Watkins et al., 2020). However, we would also argue that there is enough research showing that reading instruction can begin as early as Kindergarten. The current national program in France requires that children apprehend the alphabetic principle and begin spelling. There is no doubt that spelling should be a part of any reading curriculum given the benefits it provides to reading (Cunningham, 2001), but it seems peculiar that teachers would be told to begin spelling without any explicit reading instruction. Developing a Kindergarten-based pedagogy

that emphasizes early learning of grapheme-phoneme correspondences and reading of extremely simple decodable text may free up time for 1st grade teachers to emphasize comprehension and learning of non-transparent words. Given that only a single child asked to stop using the Kalulu software, we see no reason why children would not benefit from such an integrated early reading program. Indeed, a clear limit of the present approach is that the teaching that was provided in 1st grade was entirely disconnected with the prior reading experience that our software provided in the previous year (in France, there is little or no communication between preschool and elementary school teachers, at least concerning the talents and needs of specific children). Future research should aim to develop a more integrated computer-aided curriculum that could be adopted by the teachers and take into account reading as well as spelling readiness in kindergarten. To this aim, the guidebook that we wrote to accompany the game has since been improved and made into a student reader with class lessons, reading aloud exercises and activities, all of which follow the Kalulu software pedagogical progression.

Conclusion

It is now undisputed that phonics instruction is an essential component in learning to read. Yet teachers and scientists know that learning to read requires more than just cracking the code. For this reason, it is important that field interventions such as this one examine the many facets of when and how to teach phonics in order to go beyond tenets and provide teachers with usable school materials for concrete pedagogical guidelines. Furthermore, interventions that posit classroom gains should be evaluated using standardized tests and tested for long-term benefits. When the gains are limited to short-term benefits and simply mirror the functions that were taught, they may not be followed by any subsequent classroom-relevant benefits. By evaluating our intervention using standardized school-based measures and looking at long term outcomes, we obtained a better, if somewhat disappointing, picture of the true benefits and shortcomings of our software intervention. Obviously, much work remains to improve future implementations of the software and its integration with existing classroom practices. Working in tandem, teachers, researchers and school policy makers should all endeavor to build a system of checks-and-balances with the goal of building a curriculum that provides the best step-by-step support for teachers and the greatest impact on the child's learning.

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Table and Figure legends

Figure 1 a-d

Screenshots from the game. a) Introduction to a grapheme-phoneme correspondence (GPC) by seeing a video pronunciation of the phoneme, hearing the sound in a word with accompanying picture, tracing the grapheme in upper- and lower-case forms. After learning the GPC, different minigames are proposed to automatize learning. b) Syllable games require hearing the new sound in a syllable and finding it amongst distractors on a screen. c) Word building games require hearing a word then choosing the correct graphemes to spell the word. d) Comprehension and morphology games require reading the word silently, then making a decision of which letters in the word are a silent feature of French or deciding if a presented word exists or was made-up by the game mascot.

Figure 2 a-f

Screenshots from the game. a) Introduction to a number and its quantity by counting to the number on a game-board that highlights the linear order of the numbers, showing different quantity representations of the number and tracing the number symbol. Once the lesson is learned, children are introduced to different games to automatize number and meaning. b) Associating number name, quantity and symbol requires hearing or seeing a quantity then matching it with the correct symbol or quantity. c) Counting games require finding the correct number in a counting suite amongst distractors. d) Base-10 understanding games require associating quantity and symbol, while taking into account place value. e) Arithmetic games provide single digit addition problems. f) A number comparison task requires choosing the biggest number in a limited amount of time.

Table 1, Baseline characteristics at pretest for children that completed the intervention.

Figure 3 a-e

Group averages on language & reading tasks at the three intervention time-points. All tests improved across time. a) oral comprehension (listening to short sentence and choosing the corresponding picture), b) phoneme awareness (choosing a picture description of a word that

either starts or ends with a target word), c) letter name knowledge (hearing a letter name and choosing three different orthographic presentations (upper or lower case; print or cursive) of the correct letter amongst distractors), d) grapheme-phoneme matching (hearing a phoneme and choosing the corresponding grapheme), e) word and pseudo-word reading (average number of items read in one minute). Pairwise differences that were significant at $p < 0.05$ are highlighted (RM read/math group; MR math/read group; C control group).

Figure 4 a-e

Group averages on number & math tasks at the three intervention time-points. All tests improved across time. a) number knowledge (a combined score of matching number name ('two') and number symbol ('2') and number symbol with quantity ('**')), b) word problem solving, c) number-line. Pairwise differences that were significant at $p < 0.05$ are highlighted (RM read/math group; MR math/read group; C control group).

Figure 5 a-b

Group averages on number & math tasks at the two 1st grade evaluation time-points. Z-scores, corrected for the composite predictor from the kindergarten analysis, for each question are presented to allow for comparison across all tasks. * Highlights pairwise differences that were significant at Bonferroni $p_{corrected} < 0.01$ for reading and < 0.08 (RM read/math group; MR math/read group; C control group).

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Kalulu phonics pedagogy

a) 3-step grapheme-phoneme lesson

b) Syllable games

c) Word building games

d) Comprehension and attention to French morphology

Screenshots from the game. a) Introduction to a grapheme-phoneme correspondence (GPC) by seeing a video pronunciation of the phoneme, hearing the sound in a word with accompanying picture, tracing the grapheme in upper- and lower-case forms. After learning the GPC, different minigames are proposed to automatize learning. b) Syllable games require hearing the new sound in a syllable and finding it amongst distractors on a screen. c) Word building games require hearing a word then choosing the correct graphemes to spell the word. d) Comprehension and morphology games require reading the word silently, then making a decision of which letters in the word are a silent feature of French or deciding if a presented word exists or was made-up by the game mascot.

Figure 1

Kalulu numbers pedagogy

a) 3-step number-quantity lesson

b) Associating number name, quantity and symbol

c) Counting

d) Base-10 understanding

e) Arithmetic

f) Number comparison

Screenshots from the game. a) Introduction to a number and its quantity by counting to the number on a game-board that highlights the linear order of the numbers, showing different quantity representations of the number and tracing the number symbol. Once the lesson is learned, children are introduced to different games to automatize number and meaning. b) Associating number name, quantity and symbol requires hearing or seeing a quantity then matching it with the correct symbol or quantity. c) Counting games require finding the correct number in a counting suite amongst distractors. d) Base-10 understanding games require associating quantity and symbol, while taking into account place value. e) Arithmetic games provide single digit addition problems. f) A number comparison task requires choosing the biggest number in a limited amount of time.

Figure 2

Baseline characteristics at pretest for children that completed the intervention.

	read/ math	math/ read	control	
N=	300	320	163	
N=female	152	144	82	$\chi^2(2)=2.33, p=0.31$
Age in months	62 (3.98)	62 (3.54)	63 (3.59)	$F(2, 780)=1.21, p=0.30$
Pretest predictive measures				
visual attention	60%(.27)	63%(.29)	63% (.28)	$F(2, 780)=0.62, p=0.540$
syllable awareness	31% (.20)	31% (.20)	33% (.20)	$F(2, 780)=0.87, p=0.418$
vocabulary	42% (.28)	41% (.29)	44% (.28)	$F(2, 780)=0.63, p=0.531$
Language and literacy				
oral comprehension	49% (.30)	47% (.31)	51% (.30)	$F(2, 780)=0.93, p=0.395$
phoneme awareness	21% (.13)	22% (.16)	22% (.15)	$F(2, 780)=0.35, p=0.703$
letter-name knowledge	26% (.25)	23% (.24)	25% (.23)	$F(2, 780)=0.87, p=0.421$
GP matching	33% (.23)	32% (.24)	31% (.22)	$F(2, 780)=0.54, p=0.585$
One-minute word and pseudoword reading*	.29 (.71) n=25%	.21 (.44) n=20%	.48 (1.3) n=29%	$F(2, 780)=6.41, p=0.002$ control > r/m > m/r
Number and math knowledge				
number knowledge	67% (.23)	68% (.23)	68% (.20)	$F(2, 780)=0.33, p=0.717$
word-problem	30% (.27)	32% (.28)	30% (.27)	$F(2, 780)=0.36, p=0.695$
number-line	23% (.23)	20% (.21)	21% (.20)	$F(2, 780)=1.28, p=0.278$

* Children were not expected to know how to read at the beginning of kindergarten and only attempted the question if they could read the first two trial words, otherwise they were scored 0. The significant group effect can be attributed to the greater percentage of children that were able to attempt this question (r/m = 25%, m/r = 20%, control = 29%). However, as the average number of words read for each group was < 1, we did remove participants to create equal groups.

Table 1

Group averages on language & reading tasks at the three intervention time-points. All tests improved across time. a) oral comprehension (listening to short sentence and choosing the corresponding picture), b) phoneme awareness (choosing a picture description of a word that either starts or ends with a target word), c) letter name knowledge (hearing a letter name and choosing three different orthographic presentations (upper or lower case; print or cursive) of the correct letter amongst distractors), d) grapheme-phoneme matching (hearing a phoneme and choosing the corresponding grapheme), e) word and pseudo-word reading (average number of items read in one minute). Pairwise differences that were significant at $p < 0.05$ are highlighted (RM read/math group; MR math/read group; C control group).

Figure 3

Group averages on number & math tasks at the three intervention time-points. All tests improved across time. a) number knowledge (a combined score of matching number name ('two') and number symbol ('2') and number symbol with quantity ('**')), b) word problem solving, c) number-line. Pairwise differences that were significant at $p < 0.05$ are highlighted (RM read/math group; MR math/read group; C control group).

Figure 4

Group average z-scores on tasks from the 1st grade National Evaluations

Group averages on number & math tasks at the two 1st grade evaluation time-points. Z-scores, corrected for the composite predictor from the kindergarten analysis, for each question are presented to allow for comparison across all tasks. * Highlights pairwise differences that were significant at Bonferroni $p_{corrected} < 0.01$ for reading and $< .08$ (RM read/math group; MR math/read group; C control group).