Technology on Our Side: Using Technology for Transferring Cognitive Science to Education

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Introduction

The advent of digital technologies has transformed human life, and it has promised to transform education. Nevertheless, the contributions to education made by many relevant and widespread technologies, like radio, television, and lately PCs, tablets, and smartphones, are strongly dependent on the existence of a carefully designed curriculum respecting what is known about human learning (Hirsh-Pasek et al., 2015). There are many successful applications of different digital technologies to education, both to the academic and the socio-emotional realms (Borzekowski et al., 2019; Goldin et al., 2014; Judd & Klingberg, 2021; Mares & Pan, 2013; Nwaerondu & Thompson, 1987; Watkins & Dehaene, 2021; Watson & McIntyre, 2020; Wilson et al., 2006). As with the development of many other applications, a user-centered approach to Educational technologies is needed. In the educational milieu, the users are students, teachers, parents, and policymakers, and the technological applications need to be developed taking into account how students learn and what can be done

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about it, something that puts the topics within the realm of educational and cognitive psychology or, more broadly speaking, in the field of applied cognitive sciences known as "the learning sciences." There are many possible uses of technology in education according to which users the technologies are tailored to. For instance, the Plan Ceibal in Uruguay uses the adaptive math platform (PAM in Spanish) to help teachers create math-related activities for children and teenagers that can be used within the classrooms or at home, thanks to the distribution of laptops and tablets to all children attending public schools. These tools have been shown to be effective for part of the population (Perera & Aboal, 2018). Some other digital tools are designed to test and follow each child's progress and find the stumbling block of their learning process and can be used for both high stakes or low stakes testing. There are also the so-called educational applications that are mainly targeted to children and supposedly can help them develop some skills and competences.

Given that teacher training is expensive and takes time, the use of technology as a means to give access to education has been specially sought in third-world countries, leading sometimes to naive proposals (Arora, 2010; Mitra, 2003). This has heralded the need to have widely applicable theories of learning and cognition that can point to evidence-based educational interventions (Dehaene, 2020; Golinkoff & Hirsh-Pasek, 2016; Meltzoff et al., 2009). These theories have wide principles and specific details. The wide principles are sometimes presented as pillars (Dehaene, 2020) or easy-to-remember lists (Golinkoff & Hirsh-Pasek, 2016) but for some authors they revolve around attention, active learning, significant feedback, and consolidation, whereas others would also include social learning, meaningfulness, and joyful play. The relevance of these principles cannot be overstated, and we believe that these aspects are quite generally applicable, despite the fact that most of them have been studied in the WEIRD (Western, educated, industrialized, rich, and democratic) population (Henrich et al., 2010).

Nevertheless, there is another, more specific knowledge that particularly refers to learning specific topics like language, mathematics, science, history, or literature. These theories are in a sense more vulnerable to the WEIRDness objection. In particular, as it is discussed elsewhere in this volume, most of cognitive science and neuroscience theories have been developed based on studies of a biased sample of humanity, the so-called WEIRD population. Both in terms of ethnic and social diversity, Latin America, Africa, Asia, and Oceania have diverse populations, with different cultures and socioeconomic situations. All these dimensions affect the way information is processed and acquired, something that needs to be taken into account when designing educational interventions, especially those based on digital technologies.

In this chapter, we present three studies in order to illustrate the need to consider the specific cultural underpinnings of learning when devising and using cognitive-based technological applications. The ANS-*Puma* study presents a tablet-based intervention on mathematical skills, the *Lexiland* one presents a digital assessment of prereading skills, and the *Kalulu* study presents a tablet-based intervention on literacy acquisition (Fig. 1 and Table 1). In each study, we review how and why the particular aspects of diverse populations should be taken into account when designing the studies and interpreting the results. We believe that by considering these theoretical bases, the promise of technology for education can be fulfilled.

Fig. 1 Screenshots from the digital Apps presented in the studies. Left column: PUMA (Prueba Uruguaya de Matemáticas) presentation screen assessment (top) and Approximate Number System (ANS) assessment (bottom). Middle column: Lexiland presentation screen (top) and phonological awareness game within Lexiland (bottom). Right column: Kalulu presentation screen (top) and grapheme to phoneme mapping game within Kalulu (bottom)

Table 1 Reading, writing, and letter knowledge measured before (Pre) and after the intervention (Post)

Task	Group	Pre		N	Post		N
		Mean	SD		Mean	SD	
Writing	C	0.292	0.239	53	0.352	0.252	53
	T	0.278	0.218	43	0.347	0.231	44
Reading	C	0.455	0.371	54	0.551	0.387	52
	T	0.444	0.338	41	0.532	0.367	45
Letter knowledge	C	0.659	0.194	54	0.722	0.195	54
	T	0.659	0.205	43	0.702	0.223	43

Reading: read a list of 20 words, and we measure the proportion of correct words read. Writing: proportion of words read to the children that are correctly written. Letter knowledge is the proportion of letters from the alphabet that children can pronounce

The ANS-Puma Study: Interventions in Early Mathematics Across SES Levels

According to one current theory of mathematical cognition, there are several systems that embody mathematical knowledge and that scaffold the learning of formal mathematics (Mazzocco et al., 2011). In the field of arithmetics and early numerical competence, these so-called *core systems of knowledge* (Spelke & Kinzler, 2007) imply, at a minimum, the capacity to estimate in parallel small and even large numerosities, termed the approximate number system (ANS), and the capacity to follow a limited number of objects, the object tracking system (Le Corre & Carey, 2007; vanMarle et al., 2018). Substantial evidence suggests that both of these systems and maybe others as well are involved in the adult numerical and arithmetic capacity, although there is some controversy concerning the role these systems have in establishing the early numerical knowledge (Carey & Barner, 2019; Libertus et al., 2011; Szkudlarek & Brannon, 2017) and whether they can be stimulated to obtain better learning outcomes (Merkley et al., 2017; Park & Brannon, 2013; Valle-Lisboa et al., 2017; Wang et al., 2016).

How much of this theoretical framework applies to diverse populations, including those from lower SES countries? As it happens with many other school topics, children from lower SES social environments tend to perform poorer than their high or medium SES level peers, especially in symbolic mathematics (Sirin, 2005). If the theoretical framework applies to all populations, one would predict that those populations at greater risk of falling behind would benefit the most from interventions geared at enhancing any of the underlying systems and their connections, as enhancing the workings of these systems would increase the likelihood of developing a functioning symbolic system. With this idea in mind, we designed an intervention program to stimulate the precision of the ANS and evaluate its impact on early numerical and arithmetic competence, in a population of low and high-SES children.

The aim of the project was to determine whether a game-based, 2-week intervention on ANS could impact the learning of mathematics in children coming from low and high-SES schools. To this end we collected data from seven schools, three characterized as low-SES and four characterized as high-SES, based on a composite measure of unsatisfied basic needs of the households including maternal education, overcrowding, precarious housing, school attendance, and maternal education. A total of 454 first graders, with ages ranging from 6.42 to 8.76, took part in this study.

Both training and assessment were conducted within the classroom with the full class playing in parallel. Teachers were present but did not take part in the intervention. For the intervention program, children completed 6-minute ANS training sessions twice a week for 2 weeks for a total of four sessions. The ANS training task presented different numbers of dots on the two sides of the screen, and children had to decide which side of the screen presented a higher number of dots. Training was delivered through tablets, and data was recorded online.

The tasks we used were included in the tablet-based *Prueba Uruguaya de Matemática (PUMA),* which evaluates different mathematical skills related to number symbol knowledge. PUMA has shown a great internal validity and a strong correlation with TEMA-3 (Ginsburg & Baroody, 2003) assessments (López, De Leon, Maiche, this volume). All the tasks are presented as games. Besides formal mathematical tasks, we created games to evaluate *time discrimination,* i.e., the capacity to compare the duration of two time intervals and *digit span*, the amount of digits a child can retain in a short period of time. We also assessed *ANS acuity* by means of the standardized Panamath task (Halberda et al., 2008). The *ANS training task* consisted of asking children to decide which side of the screen presented a higher number of dots. Children completed four ANS training sessions with feedback, with a duration of 6 minutes each.

Unfortunately, data from the control group could not be completed, and thus the effects of the intervention program could not be effectively assessed. However, the collected data on the training across SES groups shed light on some of the inequities brought by SES levels, their underpinnings, and how training can affect them differentially.

Results showed that PUMA scores measuring formal math abilities differed significantly between the two SES levels, as did the ANS and time discrimination measured (for full statistical details see Valle-Lisboa et al., 2017). While, regrettably, this is not an unexpected result, we went further in trying to understand how the SES effect is mediated. In a previous work (Odic et al., 2016), we had found correlations between formal math performance and cognitive variables such as ANS and time discrimination that were partially independent of each other. This opens the question of whether ANS and/or time discrimination mediate the effect of SES on PUMA scores. Thus, we conducted a regression analysis to understand what variables explain the differences in PUMA scores. Crucially, when ANS acuity, digit span, and pre-/postassessment time were regressed together with time discrimination and SES, none time discrimination nor SES levels were significant predictors of PUMA scores. Thus, these cognitive factors somewhat mediate the effect of SES, and they change during the intervention.

The lack of a control group impedes the establishment of causal relationships. Nevertheless, by analyzing the results in the PUMA test with respect to the number of instances a child played the training games during the intervention, we evaluated whether there were any dose-related gains, as there was natural variation for external reasons (malfunctioning tablets, child absence due to sickness, etc.). The main result of this analysis showed that, besides pretest scores, doing more trials of the intervention games leads to a marginally significant increase of the PUMA score in the posttest ($p < 0.06$). Critically, the interaction of SES and number of training trials was significant, in particular with a stronger effect at the low-SES level.

Overall, the results suggest that the effects of SES can be mediated by basic cognitive abilities and that these abilities can be the target of interventions. Of course, the methodological limitations preclude us from making strong claims about the effectiveness of the interventions. In recent years there has been a set of studies questioning the effectiveness of ANS training, both empirical ones (Merkley et al., 2017) and theoretical ones (Carey & Barner, 2019). One response to these studies is to refine the theory (Spelke, 2017). In that new version of the theory, what is required to learn mathematics is not to strengthen or enhance the workings of the basic cognitive systems, but to link them to linguistic or other abilities to develop the full-fledged symbolic but grounded system of representations. In that sense, merely increasing the acuity of the ANS can only have a limited impact on symbolic mathematics. Consistent with this picture, in a recent study (Dillon et al., 2017) what worked best for enhancing mathematical knowledge was the intervention based on combining approximate and symbolic numerical representations. Likewise, several results show that the development of other notions linked to numerical knowledge, like the order representations, might have a greater impact furthering elementary mathematics learning (Lyons & Ansari, 2015). Likewise, we have recently shown that spatiotemporal conceptual knowledge predicts early mathematics above and beyond age, general vocabulary, and intelligence (Fitipalde et al., submitted). The differences in formal mathematics we found between children from low and high-SES schools can thus be traced to other more general abilities. There is a complementary interpretation of these results, though. Given the screening of the effect of SES on mathematics by ANS and digit span we reported, one might wonder whether the lack of effect some studies have found is a reflection of several of these studies being conducted in affluent countries. Then, the other response to these studies is that maybe in those societies the basic cognitive abilities are close to being saturated, but that there are other non-WEIRD countries where there might still be value in trying to promote the development of basic core cognitive abilities. This should be further studied in a preregistered manner in different populations.

The *Lexiland* Study: Learning to Read in a Transparent Orthography

Reading is a paramount skill for personal and professional development (Arnold et al., 2005). Reading, unlike language, is an acquired skill, and it requires teaching and practice for it to develop. Typically, this happens in formal school settings. The worldwide efforts to increase the number of children completing primary schooling have yielded good results, but this has not guaranteed that all of these children leave primary school reaching the expected minimum levels of proficiency in math and reading (Roser & Ortiz-Ospina, 2013). According to World Bank and UNESCO's reports, 53% of children in low- and middle-income countries fall within the category of what they call learning poverty (World Bank, 2019). Predictably, the COVID crisis has made the situation even worse, with estimates of the number of children in learning poverty escalating up to 70% (World Bank, 2021). A promising way to face this crisis is to use technology, for instance, by screening for reading difficulties early on, even before formal reading instruction begins, at times where interventions are most effective (Fletcher & Vaughn, 2009). This is possible since, for decades now, we have known that some of the prerequisites for reading acquisition start developing way before the beginning of formal reading instruction.

According to substantial evidence, one of the most relevant preliteracy skills needed for successful reading acquisition is phonological awareness, our ability to isolate and manipulate speech units (Melby-Lervåg et al., 2012). It is measured through tasks assessing the capacity to segment words into their constituent syllables or phonemes or those requiring blending phonemes to form a word, among others. In addition, children need to be familiar with the alphabetic principle, the concept that letters represent the sounds of oral language (Rayner et al., 2001). Next, children need to master letter knowledge (Foulin, 2005; Byrne & Fielding-Barnsley, 1989), that is, knowing, for each letter, which is its corresponding name or sound.

These three factors (phonological awareness, the alphabetic principle, and letter knowledge) underlie the first stage of reading acquisition, known as decoding (Hulme & Snowling, 2013). Decoding is the process by which children take each of the letters in a written word, convert it into its corresponding sound, and blend them together into a spoken word. Once they achieve this feat, they can access the word's meaning. The decoding process in its beginning is slow and effortful, thus children need to maintain each converted sound in their phonological short-term memory in order to be able to blend them into a word by the time they reach the last letter.

Two stages follow decoding in the reading acquisition process: fluency and comprehension (Nation, 2019). Fluency entails automatizing the decoding process, in order for it to be fast, precise, and effortless. It involves additional skills, mainly related to lexical access, pattern recognition, and visuo-attentional skills relevant for text processing (Kuhn et al., 2010). These factors are frequently measured through an experimental task known as rapid automatized naming (RAN). In this task, children are presented with a grid of objects, numbers, letters, or colors and are asked to name them as accurately and rapidly as possible. Taken together, phonological awareness, the alphabetic principle, letter knowledge, phonological short-term memory, and the RAN task—known as *preliteracy skills*—have been shown to be strong predictors of future reading outcomes. Since none of them requires actual reading, they can be assessed in the kindergarten years, before formal reading instruction begins.

These preliteracy skills can be used to predict and intervene promptly on those cases where it is needed (Fletcher & Vaughn, 2009). A limitation of most predictive studies is that they have been carried out either in the laboratory or by individual assessments in the school context, an approach which is not scalable, especially in under-resourced economies. The use of technology can aid in overcoming these limitations, by potentially allowing automatic autonomous assessment, carried out in groups in the school context.

With this scenario as a backdrop, in the *Lexiland* project, we aimed at developing a digital universal screener of reading difficulties targeted at children attending kindergarten. We developed an app—*Lexiland*—to assess preliteracy skills and validated its potential to predict future reading outcomes through a longitudinal follow-up study from kindergarten to second grade of 617 children from public schools in Montevideo, Uruguay. The sample was characterized as middle income (quintiles 3 and 4 of the income distribution). Children were assessed in groups of four to five at schools during school time. Since most schools did not have any extra room for assessment to take place, the assessment was done mainly in hallways or playgrounds. The research team provided the tablets with the loaded app, and two research assistants monitored data collection. All tasks' instructions and feedback (for practice trials) were prerecorded and delivered through the videogame through headphones, and research assistants were available for clarification upon demand. The initial sample of children was followed for 2 additional years, assessed at the end of first grade and the end of second grade, to evaluate their reading skills, including decoding, fluency, and comprehension.

The study resulted in both expected and unexpected findings. Among the expected, but yet novel, findings, we showed that by a brief—20 to 30 minute—assessment of only three preliteracy skills at the end of kindergarten (letter knowledge, phonological awareness, and short-term memory), we could predict future reading outcomes with high accuracy. Our model, tested through cross-validation, offered 90% sensitivity and almost 80% specificity (Zugarramurdi et al., 2022b). This high accuracy classification levels are equivalent to those reported in previous lab or individual assessment studies (Ozernov-Palchik & Gaab, 2016; Thompson et al., 2015) but remarkably in our case were produced by a group-based, in-school, autonomous assessment.

Among the unexpected findings, our study showed that the role that phonological awareness plays during reading acquisition is not as universal as previously thought. While we did find phonological awareness to predict future reading acquisition, we also found that, when considering it together with letter knowledge and verbal short-term memory, phonological awareness did not contribute any additional unique variance (Zugarramurdi et al., 2022a). These results contradict those reported for English-speaking children and add to the scarce evidence coming from non-English-based studies.

We believe that the differential contribution of phonological awareness is due to two factors. First, we found that phonological awareness at the phoneme level does not develop before reading acquisition in most children. It is possible that this is a result of the cultural environment, where the contribution of oral language skills, in general, and phonological awareness, in particular, to reading acquisition is not generally acknowledged. A large proportion of the evidence on reading acquisition comes from studies carried out in the UK, a country with a long established policy for teaching reading centered around phonics methods that assign great importance to the development of phonological awareness and letter knowledge (Machin et al., 2018; National Reading Panel, 2000) and therefore it is not surprising that phonological awareness is a strong unique predictor of future reading outcomes. On the contrary, in other countries, such as the USA or Uruguay, home environment and teaching practices are much more variable, and although the capacity to develop phonological awareness might be present, it is not consistently stimulated in schools or at home. Second, our results can be interpreted in terms of the orthographic specificities of the Spanish language. Orthographies can be characterized in terms of the consistency of the mapping between graphemes and phonemes, in a continuum from transparent to opaque. English, the most studied language in the reading acquisition literature (Share, 2008), locates in the opaque end of the continuum, where mappings are very irregular. That is, the same grapheme can have many very different associated phonemes, as exemplified by the different sounds of the letter /a/ in the words /cat/ and /table/. On the contrary, in Spanish (and similarly in Finnish or Italian), graphemes almost always map to the same sound, irrespective of the context in which it is embedded. In such transparent orthographies, learning to decode requires learning a few associations and mastering the ability to blend those sounds. Given that phonological awareness is not explicitly taught, when children are taught to read, they develop phonological awareness at the same time, which explains why it does not add unique variance to prediction. While some studies before ours have made similar points (see, e.g., Landerl et al., 2019), the bulk of the evidence has come from children learning to read in English, an opaque and atypical orthography, obscuring the diversity inherent to the reading acquisition process.

Thus, the Lexiland study highlights the great benefits of incorporating technology into education, while also providing novel infrequent evidence on the reading acquisition process from a less studied population and language.

The *Kalulu* Study: Lessons Learned From a Tablet-Based Intervention on Reading Instruction

The third study we review concerns the use of tablets in early reading instruction. The use of digital platforms is especially challenging during the end of kindergarten and beginning of first grade, where direct social interactions play a primary role in learning. In particular, learning to read depends on multiple factors, both individual and institutional, that need to be taken care of for an effective learning process. While educational institutions take all the factors into account, the traditional teaching/learning dynamic was not designed to rely upon technological tools (von Brevern, 2004).

The contributions from cognitive sciences can help in bridging this gap. There is substantial evidence about the initial steps of learning to read (see before and Cuetos, 2008; Defior et al., 2015; National Reading Panel, 2000; Perfetti & Bolger, 2004; Bradley & Bryant, 1983). In addition, several recent studies have specifically evaluated the effectiveness of incorporating technological tools for educational purposes in the domain of reading and literacy (Gaudreau et al., 2020; Kirkorian, 2018; Ojanen et al., 2015; Potier Watkins et al., 2020). These studies demonstrate that technology can help to optimize time management and organization of school work, as well as to design out effective interventions. Here, we describe the adaptation of a game—*Kalulu*—designed to enhance reading acquisition. *Kalulu*, originally developed in France, is based on accumulated evidence stemming from neuroscience research and its transfer to the field of education (Dehaene, 2011, 2014, 2015). It was designed to complement classroom teaching by using it either within the classroom or at home, and its effectiveness has recently been tested in a first experimental research study in France (Potier Watkins et al., 2020).

The game targets reading acquisition through the explicit and systematic teaching of letters and letter-sound correspondences. It presents a series of training screens, termed *lessons,* where each student receives a short explanation of the sounds and use of letters in different contexts. After this, several interactive games are presented that aim to strengthen the knowledge presented in each lesson. In this way, players learn the correspondence between graphemes and phonemes in their different forms (uppercase, lowercase, and italics) and then deepen this knowledge through the proposals of each interactive module.

Crucially, *Kalulu* presents letters in a systematic manner, from the simplest to the most complex, according to an automatic procedure that weights the consistency and frequency of different grapheme-phoneme mappings (see below). In addition to a carefully designed progression of stimuli, the game has the benefit of gradually adapting to the individual difficulties of each player, being slower when students need more time and increasing the pace for students who can handle more difficult games. Therefore, *Kalulu* offers a regulated, systematized teaching in ascending order of complexity to facilitate the decoding of words and stimulate the learning of reading in a simple and attractive way for the youngest children.

Since the progression of letters is such a critical factor and the complexity of grapheme-phoneme mappings is orthography-specific, a first step in the adaptation involved adapting the progression of stimuli to the characteristics of the Spanish orthography. For this purpose, an algorithm including a seq2seq transformer was used, which was specifically designed to map phonetic coding of words to their graphemic representation. The input to the transformer consisted of a list of 13,184 frequent Spanish words in children's books (Corral et al., 2009), with the syllabic structure and psycholinguistic properties obtained from ESPAL (Duchon et al., 2013). As a result, an ordered sequence of letters was obtained for Spanish, based on the consistency of the grapheme to phoneme mappings, from simpler to more complex ones (Potier Watkins et al., 2019), coupled with words and phrases that can be used for practice. The method produces a reasonable didactic progression. For instance, the vowels are taught in the first lessons due to their very consistent grapheme to phoneme mapping and their high frequency. On the contrary, the letter C is not taught in the first lessons because it is associated with two sounds in Spanish (/k/ and /s/); the letters X, K, and W are presented in the end due to the low frequency of use. Grapheme-phoneme mappings are presented in isolation and also in the context of frequent words.

In order to test the effectiveness of Kalulu, a randomized control study was carried out, with first grade children from five public low-SES schools in Montevideo. We choose to apply Kalulu in vulnerable contexts due to the fact that there is scientific evidence that indicates that the context can act as an influencing factor in children's reading performance (Diuk & Ferroni, 2012; Fish & Pinkerman, 2003). The study included 145 children (80 boys and 65 girls) ranging 6 to 7 years old, attending the last trimester of the school year. Children played Kalulu in tablets, individually, in the school context, in groups of five children playing in parallel, outside the classroom. Each child played twice a week, and completed at least ten 20-minute lessons. The training group played the Kalulu lessons described above, while the control group also played Kalulu but on a different path focused on mathematical skills (not described). Before and after the intervention, children were evaluated on preliteracy skills (letter knowledge and phonological awareness), verbal short-term memory, IQ, and word reading and writing, through *Lexiland* (see above and Zugarramurdi et al., 2022b). Groups were matched on phonological awareness and IQ, and no significant differences were found on letter knowledge, reading, or writing before study onset.

Results showed that all children improved in reading, writing, and letter knowledge between pre- and post-measures. However, no significant differences were found between treatment and control groups.

Since the initial lessons of Kalulu are highly focused on grapheme to phoneme mappings, and in trying to better understand the equivalent growth of literacy skills between groups, we further analyzed children's letter knowledge before the intervention began. The data showed that most children knew more than half of the letters from the alphabet. In particular, when looking at letters taught during the ten *Kalulu* lessons that children played, we found that, on average, children knew 75%, showing a ceiling effect. We believe these unexpected results stem from a discrepancy between curricula and in-classroom teaching practices. Explicitly teaching grapheme to phoneme mappings is not encouraged in the national curricula, and thus, before the study, we did not expect children to master *Kalulu's* lessons contents at the onset. However, as informally reported by the teachers taking part in the study, all participants were getting daily explicit training on grapheme-phoneme correspondences. These teachers had enough experience to know that such knowledge was essential for children to develop basic reading skills, irrespective of what the curricula suggest (or ignores). According to our previous experience with middle- and high-SES schools (Zugarramurdi et al., 2022a), it is mostly teachers from low-SES schools that insist on teaching letter knowledge and word synthesis, effectively implementing a form of synthetic phonics program. Moreover, since the intervention took place in the last trimester of the school year, children had had enough time to work on the lessons presented by the game in person with their teachers.

Surprisingly, even though children showed strong knowledge of letters and their sounds, performance in post-intervention word writing assessments showed results below 40% accuracy. Although teachers were able to work successfully on the teaching of letters, they reported that the times explicitly dedicated to the teaching of writing did not exceed 5 hours per week. In this sense, we believe that using tools such as *Kalulu* at the beginning of literacy acquisition would optimize the time devoted to the decoding process, allowing for an increase in the hours dedicated to teaching writing. This is due to the fact that *Kalulu* presents the information in an explicit and systematic way through the use of different interactive games that proved to be attractive for children, which further motivates their learning.

General Discussion and Conclusions

What the three studies presented here have in common is that they were based on the use of cognitive science to devise testing and intervention strategies using digital media. Both the mathematics intervention and the reading assessment were aimed at easing testing in school settings, one by deploying PUMA (see also López et al., this volume) and the other by creating Lexiland. The *Lexiland* study was indeed the development and validation of an assessment tool. The *Kalulu* study was intervention in the literacy acquisition process by the use of a principled way of presenting letters during the early steps of learning to read. Most of the testing tasks in this study were possible thanks to the presence of *Lexiland*, developed for the second study. *Lexiland* was also important because it was adapted to the characteristics of the local population. As explained before, one important aspect of early reading in Spanish, evidenced by the Lexiland study, which is not usually considered when dealing with more opaque writing systems, is that in a transparent orthography the most important early predictors of future reading are letter knowledge, memory, and rapid automatized naming, whereas phonological awareness, although it can be used to predict future learning to read, seems not to be a prerequisite. We believe that, in Spanish and other transparent orthographies, once letter knowledge and enough working memory are in place, learning to read is underway. To put it in another way, if a child knows the sounds of each letter and can hold them in memory, when they learn how to blend the different sounds, which is a phonological awareness task, they know how to decode. This contrasts with other orthographies, where letter knowledge, memory, and phonological awareness are not enough to be able to read most words, especially because what is measured as letter knowledge is not enough to define grapheme-phoneme mappings. Phonological awareness is thus a prerequisite in those orthographies. Although there are both transparent and opaque writing systems in WEIRD countries, most of the results in the mainstream literature come from English, whose writing is quite opaque. Thus, when we deployed our testing strategy, we remained open to the possibility that some predictors are more important than others. Notice that this does not question the main framework of the science of reading but parametrizes its application to the specifics of the culture, a conclusion that becomes especially evident when working outside WEIRD populations.

A similar parametrization applies to the PUMA-ANS study results. In effect, although the lack of a proper control group limits the interpretability of the results, the fact that there is a dose-response between training intensity and PUMA scores, and that most of the SES effects are screened by basic cognitive skills, points to an important explanatory value of these cognitive variables. What is noteworthy about the role of these variables is that most researchers in the field nowadays maintain that enhancing ANS is not enough (Dillon et al., 2017; Hyde et al., 2021) or even necessary (Carey & Barner, 2019; Lyons et al., 2014) to master elementary mathematical knowledge. This is interpreted as a result of limited association between symbolic and nonsymbolic representations of magnitudes. How can our results be interpreted? One possibility is that the range of situations that are explored in WEIRD countries is limited and so the development of ANS follows more or less the same pathway in those countries, where differences in ANS accuracy have little or no importance. In contrast, in non-WEIRD countries where poverty is more extreme, there might be cases of children with little opportunity to develop the approximate number system, making stimulation much more important. This is consistent with our results showing that children from low-SES schools gain more in math when trained with ANS stimulation. The result contrasts somewhat with those of a large study conducted in India (Dillon et al., 2017) where the authors showed no effect of non-symbolic math training in school scores. Notice that our intervention was short and that these authors use school mathematics as their dependent variable, which is a more distal measure compared to our PUMA scores. Also, the characteristics of the India population need not be equal to our Latin American schools; not all non-WEIRD countries are created equal. An attempt to partially replicate some positive findings of short interventions stimulating ANS on math in the same setting have failed to find significant results (Díaz-Simón, 2021) but these studies used extremely short interventions. The theoretical interpretations of the different sets of results remains open. Clearly, more work needs to be done.

Lastly, when we think about interventions in low-SES settings, it is important to consider which other social agents are at play in the field. Although in our country the reading curriculum is organized around an eclectic proposal mixing several aspects of a whole language approach with some phonological awareness ideas, and the inspector system strongly suggests that teachers follow these guidelines, several teachers and principals of the Kalulu study said they were following more closely a phonics-based curriculum, because, if not, children would not learn. In essence, our experience from higher SES schools was not applicable to this low-SES setting. In this sense, we only managed to repeat what they had already learned a few months before. Our next step is clear, we should start earlier and make the game more adaptive to what children already know, and not to what we expect them to know, not because they have some particular gift, but because we are not the only agents in the field.

To conclude, our three studies evidence three types of peculiarities that need to be taken into account when trying to apply cognitive science to non-WEIRD populations. In the first place, as in Lexiland, there are linguistic and more general cultural differences between different countries that need to be taken into account. Second, there might be situations where interventions in some countries use variables (like ANS accuracy) that are not elastic enough because in that particular place they are already saturated, but that in other places they might need to be enhanced; this should be analyzed in each particular case. Lastly, when applying interventions, especially in settings that receive attention from many different agents, what these other agents are doing needs to be put into the picture and dealt with appropriately. If these provisions are met, the possibility of using cognitive science to base the design of digitally based interventions is a principled way to use technology in early education settings and a particularly valuable assets in low-income countries where human and financial resources are scarce.

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