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Abstract

Mathematical concepts emerge from an early age. Although children come to the world with some innate pieces of knowledge, their abilities are further developed throughout the first years of life and later solidified by formal education. Environmental differences, such as disparate socioeconomic status (SES), are shown to have contrasting effects on math competence, with children from low SES being negatively impacted. In this chapter, we review the existing literature showing differences in early math performance across SES and the possible ways of overcoming those differences. We present some educational technologies that, used correctly, may contribute to equalizing early math knowledge. Our focus is centered on diverse technologies that have been used in school interventions conducted in Latin American countries, including an overview of past and present studies from our research group in Uruguay. Following a discussion of the positive and negative outcomes, we present some guidelines for the use of educational technologies in low SES contexts.

Keywords: mathematical cognition; educational technologies; low SES contexts.

Introduction

There is a cultural problem with mathematics. Many children, and also some adults, show an aversion towards dealing with numbers and arithmetic operations. In extreme cases, this behavior leads to stress and fear akin to a phobia, which receives the name of mathematical anxiety (Dowker et al., 2016). Unlike the social and parental pressure regarding language difficulties, which are usually corrected due to the need to read and write in order to communicate with others, struggles in math are often overlooked and accepted, particularly in underprivileged contexts (DeFlorio & Beliakoff, 2015). The consequences of poor mathematical performance are damaging and long-lasting, both for the individual and for their communities.

Data from large-scale surveys reveals significant differences in mathematical abilities across socioeconomic status (SES) (OECD, 2019). SES refers to the position of an individual or a group within society and is usually measured using household income, occupation and degree of education of parents. Low SES populations present more health problems, stress, malnutrition and domestic violence, as well as less neurocognitive and socioemotional development (Bradley & Corwyn, 2002; Noble et al., 2005) which usually results in lower academic achievement.

Traditional educational approaches have failed to reduce this academic achievement gap (Ryan et al., 2006). The recent emergence of new information and communication technologies (ICTs) can provide innovative and exciting opportunities to balance the disparities. These opportunities depend on giving students a real chance to interact with the technology, but also on the type of activity that the new technologies support in the school environment (Alderete & Formichella, 2016). While policy makers and technology investors tend to quickly align themselves behind new seemingly magical solutions, the academic community needs to make critical revisions of past and present studies and thus provide guidelines for future research and educational policies. Such is the approach of this work.

In this chapter, we discuss the role that educational technologies may play in supporting the development of mathematical cognitive skills in children, specifically those from low SES populations in Latin America. Educational technologies encompass all alternatives to traditional education based on ICTs, such as audio and video lessons, computer-assisted instruction, and digital and hybrid games. First, we review the existing evidence that shows that differences in mathematics performance across SES levels are already present in early childhood. Then, we explore some technological solutions that have been implemented in educational settings aiming to boost the math knowledge of underprivileged children. The main section of this chapter focuses on research done in Latin America around this topic. In this context,

we also present the work that our group has been carrying out with technology-based interventions in Uruguayan schools, including the main results and insights from recent years, as well as ongoing studies and future directions.

From the revision of the positive and negative outcomes of the inclusion of educational technology in Latin American schools, we shall conclude that the discussion about whether or not to use ICTs must be replaced with a discussion about how to use them. Technological tools can provide children in underprivileged contexts with some of the specific stimuli, questions, and answers that their peers in middle and high SES contexts are usually exposed to in their households.

Early math performance and SES

Mathematical concepts emerge from an early age. Although children come to the world with some innate abilities to approximately quantify entities and events (Feigenson et al., 2004; Izard et al., 2009), these abilities are further developed throughout the first stages of life (Odic et al., 2013) and later solidified by formal education (Halberda et al., 2012). Several longitudinal studies have shown strong correlations between early numerical skills and later mathematical performance (Starr et al., 2013; Gilmore et al., 2010). It is therefore essential to identify children with underdeveloped mathematical abilities and focus on boosting their competencies in those first years of life.

One source of disparity in academic achievement is SES. Children from low-SES households underperform their peers from high-SES contexts in basic mathematical knowledge as early as kindergarten (Starkey et al., 2004) which results in a "school entry gap" (Janus & Duku, 2007). Crucially, the disparities between low-SES and high-SES individuals in math are greater than those in language and other areas of knowledge (Cross et al., 2009; Duncan et al., 2007). This gap increases across the lifespan and might influence long-term academic and professional achievement.

The underlying origins for the lower math achievement in children from underprivileged contexts may be manifold. From a developmental point of view, growing up in poverty is linked with hindered physical, mental, and emotional health (Bradley & Corwyn, 2002; Yoshikawa et al., 2012). Children from low SES families show underdeveloped brain structure (Noble et al., 2005; Ursache et al., 2016). Research has made it possible to corroborate the influence of living in poverty on basic cognitive processes, such as self-regulation, and to detect its traces in adults with a past of child poverty (Lipina, 2016). Low-SES is associated with reduced vocabulary and language processing skills (Fernald et al., 2013) and lower numerical abilities

(Jordan et al., 1994) compared to their peers from middle and high SES even before the start of formal schooling. These differences subsequently increase throughout childhood and adolescence (Duncan et al., 2007) and result in higher dropout rates (Alexander et al., 1997). Furthermore, although parents from low-SES households tend to get involved in home math activities as much as parents from middle and high-SES households, the latter show higher expectations which might explain these disparities (Susperreguy et al., 2021). Parents from different contexts not only act but also think differently about the importance of math (Elliott & Bachman, 2018). Moreover, differences in math achievement might also emerge from disparate quality of home activities, suggesting that not any kind of parental involvement impacts learning equally.

However, while poverty is associated with lower school performance, differences can be observed within children from low-SES households. Halle et al. (1997) conducted interviews with low-income minority children and parents and found that mothers with higher education had higher expectations for their children's academic achievement which influenced their children's subsequent achievement in math and reading. Thus, growing up in a low-SES household does not necessarily imply low academic achievement. Consequently, and independently of the need to eradicate poverty, finding the most efficient ways to help children from underprivileged contexts learn mathematics is an effort worth making.

Can technology be the modern great equalizer?

Education is often perceived as the main tool for reducing social disparities. In the 19th century, Horace Mann defined education as the "great equalizer of conditions of men". Under this view, if all children enter a schooling system at the same age, learn the same contents, and are held to the same standards, they should finish their education at the same level and have the same opportunities, regardless of their SES. As we know, this traditional view is far from the truth. On the contrary, social context routinely influences the quality of education, which widens rather than closes the academic gap between children living in poverty and their peers from middle and high-SES. The educational policies implemented in the last century have failed to change this reality, making education a reflection of social hierarchy rather than a contributor to social mobility.

An alternative view suggests that ICTs might replace traditional educational methodologies (Bando et al., 2016; Pea, 1987), in particular as a solution for hindered development in children from low SES backgrounds. Technological tools might provide children with the specific educational content they need and thus balance

social differences. Children from underprivileged contexts can have access, through the use of computers, smartphones, and other ICTs, to a myriad of stimuli, questions, and answers that their families and schools might not be able to provide at the time they need.

In this sense, the inclusion of educational technologies in school settings or at home can balance math performance differences by compensating for specific areas in low-achieving children. In fact, technological tools can also be used to perform fast and detailed math evaluations in order to obtain detailed assessments of a child's abilities and potential areas of deficiencies. This assessment can in turn be used to improve their performance before those children fall behind their peers. Frequent testing also facilitates the retention of information (Roediger & Karpicke, 2006) but pen-and-paper tests can take too long for educators to correct. Using ICTs can not only accelerate this process, but also provide educators with opportunities for adaptive testing and result in valuable feedback about their students and what areas they should work on. Computer-based assessments are already in use in most countries for standardized tests such as PISA (OECD, 2019) and will likely be a key component in the future of education.

However, the evidence supporting the benefits of the systematic use of tablets and mobile devices in schools is still scarce (Haßler et al., 2016) with significant yet moderate effects on learning (Sung et al., 2016; Cheung & Slavin, 2013). A review of 74 studies that include the use of educational technology applications in mathematical learning shows an overall small effect size compared to traditional methods (Cheung & Slavin, 2013). The authors highlight supplemental computer-assisted instruction (CAI) as being the methodology that produces the largest effects on mathematics achievement and conclude that incorporating these educational technologies into the classroom curriculum appears to be the best approach.

Interesting observations can be made from studies comparing technology-based and traditional teaching methodologies. Outhwaite et al. (2017) report significant learning gains from tablet-based interventions in UK schools. Their results indicate that low-achieving children, in particular those with weak short-term memory skills, show the largest improvements. The authors attribute this outcome to the reduced cognitive demands of a tablet game in comparison to traditional classroom learning. When controlling for previous mathematical knowledge, the authors find no significant effect of SES level. Previous works support the idea that technological tools are useful for children with lower numerical skills (Räsänen et al., 2009; Shin et al., 2012).

Educational technologies can also be used outside school settings, particularly at home. Parental expectations, practices and attitudes towards the learning of math are known to impact a child's mathematical performance (Elliott & Bachman, 2018; Halle et al., 1997). Low-achieving students are likely not getting high-quality interactions and support at home. This may be due to parents' lack of knowledge about how to help their children or the (misleading) idea that their interactions will have no effect on their children's learning. In such cases, ICTs can provide an effective and accessible solution. Berkowitz et al. (2015) carried out an intervention to promote home math interactions with 587 children and their parents in the United States. A tablet app called *Bedtime Learning Together* presented a short story with numerical content and related questions. The story was read by parents who also answered as many questions as they wished together with their children, thus promoting the expected interaction. The questions included counting, geometry, and arithmetic. Parents used the app several times per week throughout the school year. Results show that children in the experimental group improved significantly compared to children in the control group who used a similar tool with reading rather than math content.

Insights from Latin America

Given the cultural and educational differences, it is unclear how the results from studies conducted in developed countries translate to the Latin American context. One relevant distinction between children in western, educated, industrialized, rich and democratic (WEIRD) and Latin American countries is their access to internet-based technological tools. Many studies have shown the correlation between availability of Internet connection and various household or individual socio-economic characteristics, such as income and education (see Grazzi & Vergara, 2014). For this reason, it is important to understand how the use of educational technologies impacts the learning in Latin American children, in particular those from peripheral and low-SES contexts.

One rudimentary yet powerful educational technology is audio. Radio lessons were popular in the 1980s, mainly as a widespread and inexpensive teaching mechanism for children in rural areas in Central America (Jamison et al., 1981), and again during the COVID-19 pandemic in regions where children lacked the internet connectivity to attend classes remotely (Dreesen et al., 2020). Naslund-Hadley et al. (2014) explored the benefits of a pilot audio version of Tikichuela, a Paraguayan mathematical instruction program for preschool children adapted from the Big Math for Little Kids program used in low-income schools in New York. These audio lessons included games, songs and interactive activities intended to capture the interest of children. The results from this study show an improvement in test scores for children

participating in the pilot program in comparison to controls following a five-month period with significantly larger improvements in rural versus urban schools but no differences on SES. The authors highlight audio lessons as an encouraging tool to reduce student learning disparities that emerge from educators lacking specific training or resources. Audio-based mathematical instruction was also used to improve the memory and math abilities of blind children in Chile (Sánchez & Flores, 2005); Cuba's video-based reading and writing program "Yo, sí puedo" has been implemented in 28 countries world-wide and has helped eradicate adult illiteracy in Venezuela and Bolivia among others (Canavire, 2011). In sum, audiovisual tools such as these are good examples of the potential for ICTs in critical situations, when other alternatives are not available.

More recently, the wide access to computers has inspired researchers to explore the educational benefits of using computer games. Goldin et al. (2014) implemented a 10-week long intervention using the *Mate Marote* software with 111 low-SES first graders in Argentina. Children played three different computer games involving executive functions which resulted in significant improvements in inhibitory control and attention, but not planning, in pretest-posttest measures compared to a control group that played commercial video games. What is more, training their executive functions resulted in a far transfer to math and language abilities, as measured by school grades. The researchers also split the children who used Mate Marote into two categories according to their attendance to school. Following the intervention, children with low attendance, who initially had lower school grades than their high attendance peers, showed the largest improvements in school grades even though they were not directly trained in language or mathematics. Other uses of educational software in Mexico (Zaldívar-Colado et al., 2017) and Argentina (Furman et al., 2019) also support the use of ICTs, although the latter showed no significant differences between groups of children that learned science with and without tablets.

Motivated by these possibilities, several Latin American governments resorted to the One Laptop Per Child (OLPC) program as a remedy for their ailing educational systems. The outcomes are ambiguous. The OLPC initiative was created in 2005 with the idea that distributing low-cost hardware that children could take home would reduce the emerging digital gap between developed and developing countries. As a side effect, the inclusion of ICTs in classrooms could have a positive impact on academic performance. Data from the educational benefits of using laptops at schools are controversial. While OLPC advertises their products with test scores from Nicaragua that showed an increase in math and reading skills, more rigorous studies conducted in Latin America do not show positive outcomes. For example, a large-scale randomized study with data from 15 months of use of OLPC devices in 318 primary schools in Perú resulted in no effects on math and language test scores, and a

non-significant increase in cognitive skills (Cristia et al., 2017). Other smaller-scale studies conducted in Perú revealed that computer skills improved in children that received OLPC devices but with no significant differences on academic achievement (Beuermann et al., 2015; Malamud et al., 2019; Severín & Capota, 2011). Similarly disappointing results were obtained from OLPC programs in Colombia (Severín & Capota, 2011), Costa Rica (Meza-Cordero, 2017), Paraguay (Ames, 2013), and Uruguay (de Melo et al., 2014; Yanguas, 2020). While it is undoubtedly beneficial that children improve their computer skills, the lack of transfer to math and language proficiency reveals that the naive approach of the OLPC program is insufficient to produce profound changes in education.

In sum, educational technologies have been used in Latin American schools with varying degrees of success. Besides the extreme cases where alternatives to traditional lessons had to be implemented because in-person classes were nonviable, positive outcomes were obtained mainly through the use of software especially designed by researchers and educators to train basic cognitive abilities. On the other hand, the unrestricted inclusion of laptops and tablets from the OLPC program showed no positive effects when it was not supported by a well-structured educational platform. This could show that it is not the technological tool in itself, but rather the use that is given to it, that allows for enhanced learning.

In this sense, we think focus must be shifted from a comparison between tech-based and traditional learning to a comparison between the contents that can be taught with each of these methodologies. Technology presents innovative, widespread, and efficient ways to include contents based on the principles of educational neuroscience in school settings which can result in improvements in academic performance (Goldin et al., 2014). The shift in focus is further supported by data about the massive and unrestricted inclusion of ICTs in Latin American schools. To illustrate this, in the next section, we present a detailed account of the work our research group has made over the last decade in Uruguayan schools.

Learnings from a decade of technology-based school interventions in Uruguay

In 2007, the Uruguayan government and OLPC partnered to establish the Plan Ceibal, a program that provides every school-aged student with an Android-based tablet that they can use at school and at home. The students have free internet connection in schools and multiple public areas around the country. This makes Uruguay an ideal site for studying the usefulness of ICTs in educational contexts.

Our research group has been working in collaboration with the Plan Ceibal for nearly ten years. We have worked on a number of projects involving technology-based interventions in classrooms that can be clustered into two main categories. On the one hand, we have designed and tested early assessment tools that can be used directly from the Plan Ceibal tablets available in Uruguayan schools. On the other hand, we have created several games aimed at reinforcing the basic mathematical abilities of young children. All the software developed by our group is free and available to everyone[1]. These tools are targeted to Uruguayan children, involving characters, places, stories, and vocabulary that they can identify with (see Outhwaite et al., 2020). From the personal reports of educators, parents, and the children themselves, this makes our games more entertaining and engaging than other educational software available in Plan Ceibal. The simultaneous use of both testing and training learning tools has shown beneficial results, particularly in low SES contexts. Our long-term goal is to incorporate a set of applications into the Plan Ceibal tablets that the teachers themselves can use to facilitate mathematical learning in the classroom.

To the best of our knowledge, there is a lack of digital math assessment tools for children under the age of 7. One of the most used tests for assessing young children in math is TEMA-3 (Ginsburg & Baroody, 2003), which takes around 30 minutes to complete and requires one-on-one interactions between a trained evaluator and each child. Although TEMA-3 is a powerful tool, it requires an amount of time and training that makes it unreasonable for large-scale interventions and regular use in schools. Our group has always been concerned with the need for tools that make testing fast and scalable, and that can ultimately give teachers useful feedback about the particular topics that require attention. For this reason, in 2013 we began the development of the Prueba Uruguaya de Matemática (PUMA), a digital tool where children are tested on their knowledge of number symbols, ordering, number composition and decomposition, number line placing, and number words (see Odic et al., 2016) for a description of the first version of PUMA). PUMA provides self-administered assessment that a single researcher or teacher can apply simultaneously to an entire class. A second version of PUMA was developed in 2020[2] with improved design and usability (Fig. 1). An assessment of 187 Uruguayan preschoolers and first-graders with the updated version of PUMA and TEMA-3 showed a strong correlation ($r=0.803$, $p<0.001$; De León et al., in prep). These positive outcomes show that ICTs have great potential regarding assessments. However, so far we have failed to convince educators and policymakers about the benefit of incorporating PUMA into regular school programs. We attribute this to a failure on our

[1] For more information go to: http://www.cognicionnumerica.psico.edu.uy/en/#recursos
[2] A demo version is available here: http://math.psico.edu.uy/puma/

part to translate the quantitative outputs of PUMA into easily understandable qualitative feedback. This must be a key point to address in the near future.

[Figure 1 around here]

The first large-scale intervention that we conducted using Plan Ceibal tablets took place in 2013. We tested 503 Uruguayan first graders from 10 schools across SES levels on their abilities to discriminate approximate quantities, using the Panamath software (Halberda et al., 2008), and approximate time (Odic et al., 2016). We also assessed their formal mathematical performance with the first version of PUMA. Our results showed correlations between math performance and approximate number discrimination as well as approximate time discrimination. Most importantly, this first large-scale use of the Plan Ceibal tablets for doing research in school settings confirmed the validity of ICTs as assessment tools. 454 of those children participated in a short intervention consisting of four six-minute sessions of approximate number system (ANS) training (Valle-Lisboa et al., 2016). Pretest-posttest differences revealed that children across all SES levels improved their ANS and formal math skills without significant differences on SES. However, only low-SES children showed a significant correlation between the number of times they played and the PUMA scores improvement. This could show that cognitive stimulation plays a higher role in underprivileged contexts. The learnings from these initial studies were in line with other studies conducted in Latin America. ICTs can be useful to assess and train the math abilities of children as long as they make use of specific stimuli designed to improve the building blocks of mathematical knowledge.

Subsequently, our emphasis veered to studying different types of stimuli that might improve math abilities. Langfus et al. (2019) conducted a five week intervention with 386 Uruguay children. Half of them were assigned to the active group and played digital mini-games on the Plan Ceibal tablets consisting of approximate number discrimination, time discrimination, and area discrimination; the other half was a Business-As-Usual (BAU) control group. For this study, we administered pre and post tests of basic and formal math knowledge as well as language and general cognitive abilities. However, the playing time was determined by the teachers, who agreed to use the games during their classes, and by the children themselves, who were encouraged to continue playing at home. No significant differences were found between the active and the control groups. A detailed analysis of the data indicates that this was likely due to the low number of plays: on average, children played the time, number and area games only 10, 16, and 26 times respectively over a five-week period. The children had positive comments about the games, but they were not interested enough to continue playing in their spare time. This highlights a particular difficulty with tech-based learning. If children are expected to engage in educational

games voluntarily, then these games must be as engaging and attractive as other commercial games that they may be used to. Alternatively, tech-based learning must be framed within well-structured activities. Educators should be trained on how to make the most of educational technologies so that children can be cognitively stimulated with stimuli specifically designed for them.

Currently, we are also interested in exploring the differences between individual and social learning. Tablets and computers are most useful for single users, but the peer interactions that usually emerge in group settings have powerful influences on early cognition and learning (de la Hera et al., 2019; Dillon et al., 2017). To this end, we designed a new game based on the cards used by Dillon et al. (2017), with a digital version that can be played individually on tablets and a hybrid version that can be played individually or collectively with a Magic Box (see Fig. 2). That latter consists of playing cards equipped with RFID tags and an Arduino-powered smart box with RFID readers. This hybrid version of the game incorporates ICTs without isolating the children and, since it promotes peer interaction to advance in the game, is predicted to be most useful in school environments, whereas individual games such as the digital version of the game can be used at home. A comparative study of 266 children with two active groups, one playing with the Magic Box and the other one with tablets, and a BAU control group, is scheduled for late 2021.

[Figure 2 around here]

In sum, the trajectory followed by our research group is representative of the general approach to educational technologies in Latin America and in the rest of the world. Our initial enthusiasm for the use of ICTs in schools, backed by large governmental investments in tech-based learning programs such as OLPC programs like Plan Ceibal in Uruguay, morphed into a critical examination of the differences between educational technologies and other methodologies, with a particular focus on characterizing the cognitive stimuli which produce the most efficient learning.

Conclusions and perspectives

The evidence presented in this chapter reveals that, while SES strongly correlates with academic achievement, it is possible to boost low-SES children's math learning by improving the cognitive abilities that support math development. Educational technologies were initially thought to be a possible solution for these disparities, but most research shows no SES-related differences between ICTs and traditional methodologies when initial performance is controlled for. That is, educational technologies are most useful for low-achieving children, regardless of their SES. By

way of illustration, it is not a households' income that determines the child's academic performance but rather the parental expectations and quality of home learning activities. In our view, this is because it is not poverty itself, but rather the individual, parental, and social consequences of poverty that are at the core of the disparity in math achievement. Even though technology cannot directly change the contexts where children from low-SES live and grow, it might compensate for the lack of math related home activities by providing the stimuli needed for their cognitive development. Thus, ICTs are likely most useful in such contexts.

Positive and negative outcomes have been observed from the use of educational technologies in Latin America. The unrestricted inclusion of ICTs in classrooms, as is the case with the OLPC program, resulted in no measurable differences in achievement other than computer and internet skills. Conversely, numerous school interventions carried out by research groups did produce significant improvements in math performance. This must lead to a shift in focus, not only for the academic community but also for educators and policymakers, about the use of ICTs. Educational technology cannot be, on its own, the modern great equalizer. But with the addition of well-structured programs that result in games and educational software with specific stimuli aimed at training basic cognitive skills, ICTs can help low-achieving children and particularly those from low-SES.

The future of educational technologies is promising but not without its challenges. First, researchers must continue studying basic cognition in the early stages of life to determine the best specific stimuli to improve learning. We also need to connect the use of these stimuli with realistic educational practices in schools and homes in order to involve teachers and parents in the learning process. This must include studies about how to include ICTs in classrooms and homes. The involvement of teachers as researchers vastly broadens the inputs of information and new ideas needed to advance knowledge. Put together with the versatility of ICTs, this joint work can allow for the exploration of multiple possibilities and can provide high-quality feedback about the impact of educational technologies in the classroom. On a similar note, researchers should aim to increase and improve the involvement of parents and other family members through the use of ICTs. This requires the development of tools that are suitable for use at home and promote the natural interaction with children about everyday math. Finally, all the software must be engaging and relatable to the children's reality, which increases the requirements and potentially the costs of developing new tools. Collaborative work with countries that share a common culture, as is the case in Latin America, is a much needed approach.

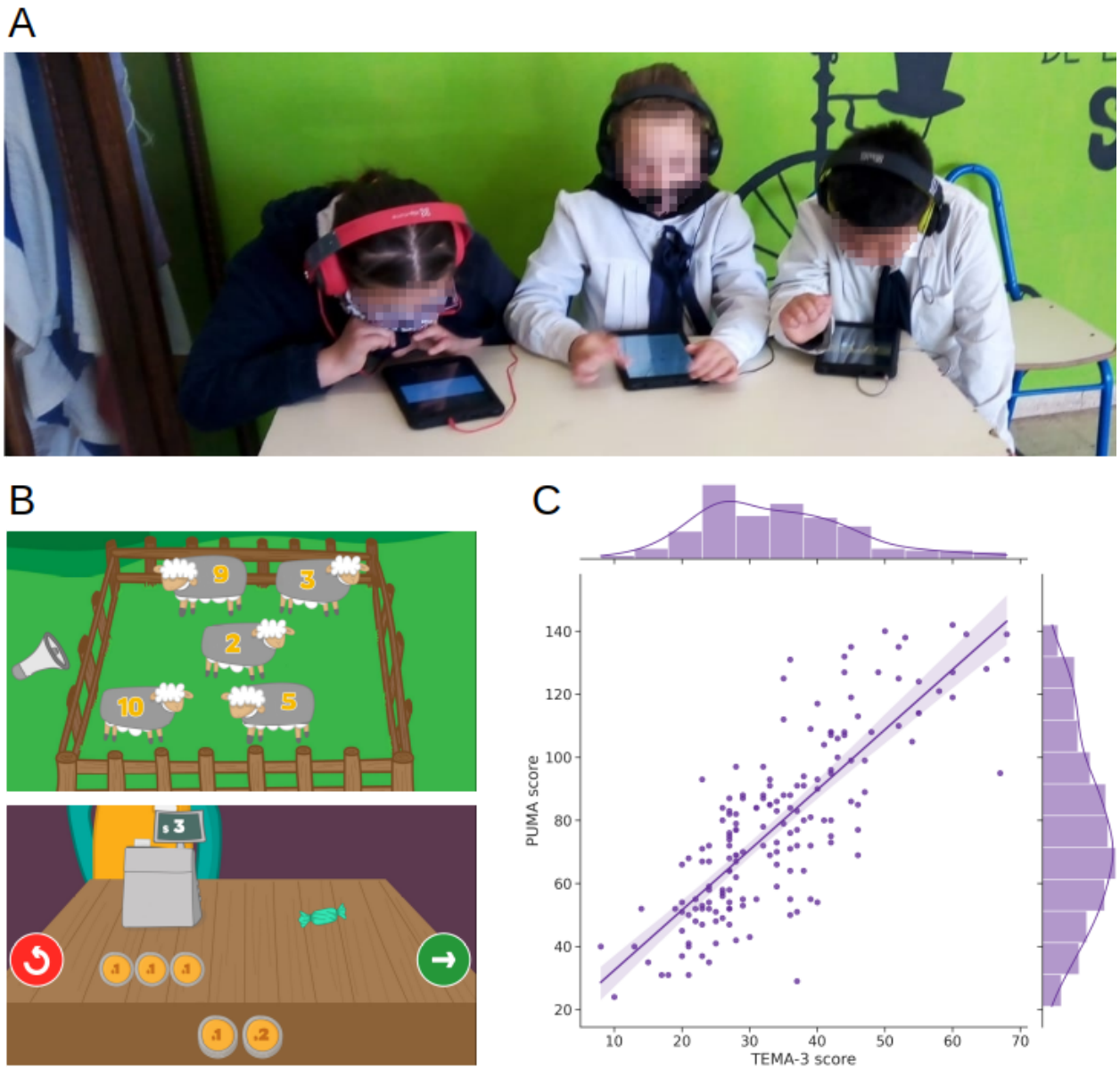

Fig. 1 - Second version of the Prueba Uruguaya de Matemática (PUMA). A: Three Uruguayan children taking the PUMA test with their Plan Ceibal tablets. B: Screenshots of two PUMA tasks (top: verbal-numeral to arabic transcoding; bottom: composition and decomposition). C: Correlation of the 2nd version of PUMA and TEMA-3 (Ginsburg & Baroody, 2003) with N=187, r=0.803 ($p<0.001$). Both tests take a similar time to complete, but PUMA is a tablet-based assessment that does not require one-on-one interactions between each child and one evaluator. It can therefore be applied simultaneously to a large number of children, e.g. an entire class could be detailed assessed in less than one hour.

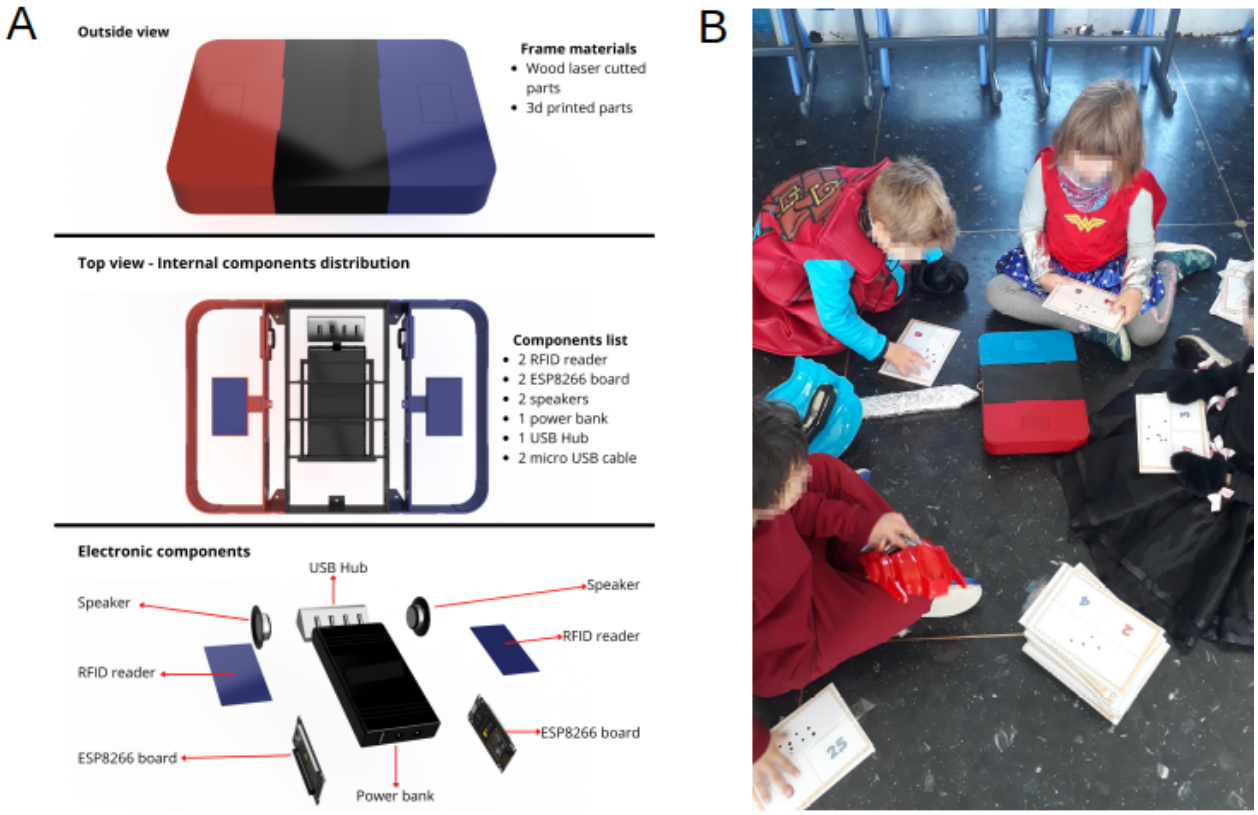

Fig. 2 - The Magic Box. A: outside and inside views of the Magic Box and its components. Note that the box is closed while playing so children do not have access to any of the internal components. **B:** A typical situation of 4 children playing in the collective version of the game with the Magic Box. Children take turns to decide whether each of their cards should go on the red or the blue half of the box. After 4 cards (one for each child) the Magic Box gives a positive feedback sound (if all 4 cards are correct) or a negative feedback sound (if at least one of the cards is wrong). Children are encouraged to interact and help each other in order to obtain a correct response from the Magic Box and advance in the game.

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