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ARTICLE

COGNITIVE SKILLS AS PREDICTORS OF ARITHMETIC ACHIEVEMENT OF 3th AND 4th GRADERS [1]

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ABSTRACT: This article presents a study that aimed to identify general and specific cognitive skills as predictors of arithmetic achievement. Through a quantitative analysis, we evaluated 127 students in the 3rd and 4th grades on the following skills: working memory, phonemic awareness, reading comprehension, number transcoding, number line estimation, and quantitative reasoning. We assessed these cognitive skills in two moments, at the beginning and the end of the school year. In this second moment, we also assessed the students' arithmetic achievement. The results specifically indicated a direct influence of number transcoding, quantitative reasoning, and phonemic awareness on arithmetic performance. In addition, the findings showed that number transcoding is a mediator in the relation between quantitative reasoning and phonemic awareness with arithmetic performance. Thus, we emphasize the importance of general and specific skills for students' arithmetic performance. Furthermore, we highlight the prioritization of teaching based on the understanding of the number system and the relations between amounts (quantitative reasoning) for arithmetic learning, as well as for preventing future mathematical difficulties.

Keywords: predictive skills, arithmetic achievement, number transcoding, quantitative reasoning, phonemic awareness.

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HABILIDADES COGNITIVAS PREDITORAS DO DESEMPENHO ARITMÉTICO DE CRIANÇAS DE 3º E 4º ANOS DO ENSINO FUNDAMENTAL

RESUMO: Neste artigo, é apresentado um estudo que se propõe a identificar, de forma quantitativa, habilidades cognitivas, de domínio geral e específico, como preditoras do desempenho aritmético de 127 alunos de 3º e 4º anos do ensino fundamental. Os participantes foram avaliados nas habilidades de memória de trabalho, consciência fonêmica, compreensão leitora, transcodificação numérica, estimativa numérica e raciocínio quantitativo. Essas habilidades cognitivas foram avaliadas em dois momentos, no início e no final do ano letivo, sendo, nesse segundo momento, também avaliado o desempenho aritmético dos estudantes. Os resultados indicaram uma influência direta especificamente da transcodificação numérica, do raciocínio quantitativo e da consciência fonêmica no desempenho aritmético. Além disso, os achados mostraram que a transcodificação numérica é uma habilidade mediadora da relação das habilidades de raciocínio quantitativo e consciência fonêmica com a habilidade aritmética. Com isso, ressalta-se a importância de habilidades de domínio geral e específico para o desempenho aritmético dos estudantes. Destaca-se também a priorização do ensino pautado na compreensão do sistema numérico e das relações entre quantidades (raciocínio quantitativo) para a aprendizagem aritmética, bem como para a prevenção de dificuldades matemáticas futuras.

Palavras-chave: habilidades preditoras, desempenho aritmético, transcodificação numérica, raciocínio quantitativo, consciência fonêmica.

HABILIDADES COGNITIVAS PREDICTORAS DEL DESEMPEÑO ARITMÉTICO DE NIÑOS DE 3º Y 4º AÑOS DE PRIMARIA

RESUMEN: Este artículo presenta un estudio cuantitativo que tiene como objetivo identificar las habilidades cognitivas, de dominio general y específico, como predictoras del desempeño aritmético de 127 estudiantes del 3º y 4º años de primaria. Los participantes fueron evaluados en las habilidades de memoria de trabajo, conciencia fonémica, comprensión lectora, transcodificación numérica, estimación numérica y raciocinio cuantitativo. Estas habilidades cognitivas fueron evaluadas en dos momentos, al inicio y al final del año escolar, y en este segundo momento también se evaluó el desempeño aritmético de los estudiantes. Los resultados indicaron una influencia directa específicamente de la transcodificación numérica, del raciocinio cuantitativo y de la conciencia fonémica en el desempeño aritmético. Con eso, los hallazgos mostraron que la transcodificación numérica es una habilidad mediadora de la relación entre el raciocinio cuantitativo y la conciencia fonémica en la aritmética. Así, se enfatiza la importancia de las habilidades generales y específicas para el desempeño aritmético de los estudiantes. También se destaca la priorización de la enseñanza basada en la comprensión del sistema numérico y en las relaciones entre cantidades (raciocinio cuantitativo) para el aprendizaje aritmético, así como para la prevención de futuras dificultades matemáticas.

Palabras clave: habilidades predictoras, desempeño aritmético, transcodificación numérica, raciocinio cuantitativo, conciencia fonémica.

INTRODUCTION

In the last decade, there has been a growing interest in numerical cognition research in identifying cognitive skills that underlie mathematical performance (NOGUES; DORNELES, 2021). Knowing which skills are involved in the development of mathematical understanding is a fundamental way to think about adequate and targeted interventions to help to learn in this area. Also, this understanding can support education professionals in identifying children who are at risk of developing math learning difficulties.

Many factors have been identified as important for mathematical performance, which includes both general domain skills, which refer to general domain cognitive abilities and which are related to diverse academic competencies, such as reading, writing, and mathematics, and domain-specific ones, which are considered capabilities that contribute to performance in a specific school competence (ARAGÓN et al., 2019; PASSOLUNGHI; LANFRANCHI, 2012; XENIDOU-DERVOU et al., 2018). In addition, it is also important to know the causality of students' mathematical performance, that is, which cognitive abilities explain this performance and can exert influence to determine a low or high performance in this area.

In this sense, some research already suggests which cognitive abilities can explain later mathematical performance (GEARY, 2011; GILMORE et al., 2018; HABERMANN et al., 2020; NUNES et al., 2007). Among the general domain skills, evidence highlights working memory (ARAGÓN et al., 2019; GEARY, 2011; PASSOLUNGHI; LANFRANCHI, 2012), spatial skills (CARR et al., 2020; HAWES et al., 2019), processing speed (ARAGÓN et al., 2019; GEARY, 2011; PASSOLUNGHI; LANFRANCHI, 2012) and phonological awareness, which includes phonemic awareness (HECHT et al., 2001; SIMMONS; SINGLETON; HORNE, 2008), as predictors of mathematical performance. Regarding specific domain skills, many studies indicate basic numerical skills as predictors such as counting (CHING; NUNES, 2017; DESOETE et al., 2009; GEARY, 2011), number recognition, also called number transcoding (HABERMANN et al., 2020; KISS; NELSON; CHRIST, 2019; MALONE; BURGOYNE; HULME, 2019), and the number line estimation (ARAGÓN et al., 2019; GILMORE et al., 2018; SASANGUIE; VAN DEN BUSSCHE; REYNVOET, 2012), as well as skill in addition and subtraction calculations, arithmetic fact retrieval and quantitative reasoning (CASEY et al., 2017; KISS; NELSON; CHRIST, 2019; MALONE; BURGOYNE; HULME, 2019; NUNES et al., 2012).

However, some skills still lack evidence about their relationship with arithmetic, for example, the skills of reading words and reading comprehension. Studies suggest that reading isolated words is a predictor of arithmetic performance (FUCHS et al., 2006; WONG; HO, 2017), indicating that decoding and word recognition are directly related to the ability to solve arithmetic calculations. Reading comprehension also seems to influence the resolution of arithmetic calculations and the retrieval of arithmetic facts (ANDERSSON, 2008). Even so, evidence about this influence is scarce, and therefore, more studies are needed to elucidate the relationship between reading and reading comprehension and arithmetic.

In an attempt to investigate the skills that influence later mathematical performance, research focuses on assessing such skills at the beginning of students' school life to analyze their influence on mathematical performance one or two years later (HABERMANN et al., 2020; MALONE; BURGOYNE; HULME, 2019; PASSOLUNGHI; LANFRANCHI, 2012; XENIDOU-DERVOU et al., 2018). However, it is also important to verify how these relationships occur in children who have been inserted in the school context for a longer time, including in already literate students, which will allow identifying more complex abilities of mathematical performance.

Therefore, this study proposes to identify general and specific domain skills as predictors of the arithmetic performance of students in the 3rd and 4th grades of elementary school. For this, some cognitive skills were selected based on research evidence that indicates significant influence values of these skills on arithmetic performance. Furthermore, this choice was made considering both general and specific domain skills that had tasks that could be quickly applied to conduct assessments within the school context. Thus, a battery of tests relating to working memory, phonemic awareness, reading comprehension, number transcoding, number line estimation, and quantitative reasoning skills was used to assess students' ability in these measures. Then, the relationships between performance on these tasks and an arithmetic task were investigated. It is also noteworthy that the mathematical performances considered as an outcome variable in the literature range from just simple arithmetic calculations to combined measures of arithmetic, problem-solving, and geometry, for example, to define a measure of general mathematical performance. In the study presented here, the focus will be on arithmetic performance, that is, the ability to solve calculations with the four fundamental operations: addition, subtraction, multiplication, and division. Such an approach is in line with what is most addressed in the mathematics subject offered in Brazilian schools, in addition to being the main focus of the Brazilian school curriculum, referring to this area of knowledge, in this stage of the initial years of schooling (BRASIL, 2018).

In the following sections, the theoretical basis for this study is presented, providing an overview of the evidence on the role of selected cognitive skills in mathematical learning in the early years of school.

General Domain Predictors

Many studies have focused on the analysis of mathematical performance predictors with the aim of elucidating which cognitive skills underlie this performance and are possible to identify students at risk of developing mathematical learning difficulties (ARAGÓN et al., 2019; GEARY, 2011; PASSOLUNGHI; LANFRANCHI, 2012). This identification can facilitate the implementation of remediation and prevention measures for mathematical difficulties with benefits, including in the long term.

Thus, a skill that is highly evaluated in these studies is working memory, which refers to a system, that is a "workspace" of memory that stores and processes information immediately or for a short period when performing cognitive tasks. (BADDELEY, 2011; PASSOLUNGHI; VERCELLONI; SCHADEE, 2007; XENIDOU-DERVOU et al., 2018). In this study, we adopted the theoretical model of Baddeley and Hitch (1974), which presents working memory as a system composed of three components: the phonological loop, which temporarily stores verbal and auditory information, the visuospatial sketchpad for the temporary storage of information visual and spatial, and the central executive, responsible for coordinating and processing the information retained by the other two components. Even with a more recent update of this model (BADDELEY, 2000), which considers a fourth component, the episodic buffer, the previous model was chosen due to the theoretical consistency and availability of tasks for evaluation (CANÁRIO; NUNES, 2012; GATHERCOLE, 2008; NOBRE et al., 2013).

Much of the research has shown that working memory is related to various mathematical skills, from counting to arithmetic calculations (ARAGÓN et al., 2019; GEARY, 2011; PASSOLUNGHI; VERCELLONI; SCHADEE, 2007). In addition, studies indicate working memory as a precursor to mathematical learning, especially in the first years of school (ARAGÓN et al., 2019; PASSOLUNGHI; VERCELLONI; SCHADEE, 2007; XENIDOU-DERVOU et al., 2018), reducing its influence as the student's knowledge matures (CHU; VANMARLE; GEARY, 2016; GEARY, 2011).

Solving mathematical tasks requires the processing of verbal and visuospatial information, as they require multi-step solution procedures. Therefore, it is not surprising that working memory plays a key role in both arithmetic and general mathematical performance (XENIDOU-DERVOU et al., 2018), as it is also a convenient skill for retaining relevant information during a calculation or while interpreting the statement of a problem to access long-term information, remember arithmetic facts and to represent the problem (ARAGÓN et al., 2019).

The relationship between the performance in working memory and in tests that assess numerical and mathematical competence has already been reported and established in the literature (GEARY, 2011; GEARY; HOARD; HAMSON, 1999). Even when evaluated simultaneously or years later, evidence indicates that the greater the working memory capacity, the better the performance in math tasks (BULL; ESPY; WIEBE, 2008; PASSOLUNGHI; VERCELLONI; SCHADEE, 2007). However, some studies show that working memory effects may also appear indirectly related to mathematical performance when numerical skills are jointly assessed. Thus, the prediction effect prevails for these initial numerical skills, but their relationship is mediated by them in later mathematical performance (FUHS; HORNBURG; MCNEIL, 2016; PASSOLUNGHI; LANFRANCHI, 2012).

The phonological awareness skill is defined as the ability to segment words into smaller units, that is, focusing and separating words into the sounds that constitute them. Phonological awareness can be separated into three main levels: syllable awareness, rhyme awareness (intrasyllabic), and phoneme awareness (phonemic awareness) (GILLON, 2017; SOARES, 2019). The latter is considered the most advanced level of phonological awareness, as it is the understanding that words are composed of individual sounds (GILLON, 2017), achieved through the association between grapheme (letter) and its respective phoneme (sound) (SOARES, 2019). In this sense, because phonemic awareness is the highest level of phonological awareness, it was decided to evaluate it in this study as a representative measure of phonological awareness. There is no consensus among the studies that considered such ability as a predictor of mathematical performance. Some studies that evaluated phonological awareness, and more specifically phonemic awareness, found a direct relationship with mathematical performance (HECHT et al., 2001; LOPES-SILVA et al., 2014; 2016), while others did not find any relationship (PASSOLUNGHI; LANFRANCHI, 2012; PASSOLUNGHI; VERCELLONI; SCHADEE, 2007). Phonemic coding of verbal numerals is the first step in number transcoding procedures, even before using algorithm rules and retrieving facts from long-term memory (LOPES-SILVA et al., 2014). Therefore, limitations in the phonological processing capacity may restrict the number transcoding capacity, particularly in the case of numbers of larger magnitudes (LOPES-SILVA et al., 2014).

The evidence that indicates the association of phonological awareness with mathematical performance also includes a causal relationship, that is, phonological awareness plays a role of influence specifically in the resolution of arithmetic calculations. For example, when solving a calculation, the student can first convert the problem terms, values, and operations into speech-based code. The use of Arabic to verbal translation is quite common in children when solving arithmetic tasks, as they will need to process this phonological information to carry out their strategy. For example, in the “5x2” calculation, the child will seek an answer based on a phonological code from long-term memory (GEARY; HOARD; HAMSON, 1999). When resorting to a counting-based strategy, the phonological system will be activated when the names of numbers (phonological numerical codes) are used to count (HECHT et al., 2001).

In a US study, 201 children were followed up from the 2nd to the 5th grade of elementary school and assessed for their phonological processing capacity, which covered three areas: naming speed, phonological memory, and phonological awareness. From this, the authors verified the influence of this skill on the students' arithmetic performance throughout these school years. It was possible to verify that phonological processing was an important predictor in the increase of the children's arithmetic performance in all the evaluated school years, but specifically, phonological awareness had the highest predictive value among the other areas of phonological processing. Furthermore, phonological awareness presented a unique predictive contribution to performance from the 3rd to the 4th grade and from the 4th to the 5th grade (HECHT et al., 2001).

The ability to understand and deal with information is a relevant factor for all the skills described, as well as for mathematical performance. In this sense, reading comprehension can be an important skill to identify children's ability to deal with information. Another US study that evaluated specific predictors for problem-solving in the early school years indicated reading comprehension as a significant skill capable of predicting problem-solving ability (DECKER; ROBERTS, 2015). Regarding arithmetic performance, some evidence points to the ability to read words being related to performance in solving calculations (GILLIGAN; FLOURI; FARRAN, 2017; WONG; HO, 2017). A Swedish study, concerned with specifically investigating the predictive relationship of working memory on arithmetic performance also considered a measure of reading comprehension among the evaluated variables. In this study, 141 students from the 3rd and 4th grades were evaluated and the results indicated that reading comprehension appeared as one of the predictive skills of performance in arithmetic calculations, being the most important for the retrieval of arithmetic facts (ANDERSSON, 2008).

Therefore, the association of general domain cognitive skills with mathematical performance can be seen, with early stimulation being very important for the development of numerical learning and for the prevention of difficulties in this area. Therefore, this study aimed to investigate the influence of the skills described above on the arithmetic performance of Brazilian students.

Domain Specific Predictors

Knowing the cognitive skills that form the basis of children's mathematical development is fundamental both for the scientific community and for educational practice. There is considerable evidence of some domain-specific skills involved in mathematical knowledge. In particular, the literature indicates that early numerical skills, even when assessed at an early age, are important predictors of later mathematical performance, both at early and late levels of school (CHING; NUNES, 2017; HABERMANN et al., 2020; KISS; NELSON; CHRIST, 2019; KRAJEWSKI; SCHNEIDER, 2009). Therefore, providing a consistent basis of mathematical competence is important for school success (CHING; NUNES, 2017), which can benefit student performance at various levels of school and favor learning more advanced mathematics content.

Among the initial numerical skills, in this study, number transcoding and number line estimation stand out as important predictors for arithmetic performance, specifically. Number transcoding is considered the notation capacity of numerical symbols from the conversion between verbal and written languages (MOURA et al., 2015). Evidence on the relationship between number transcoding and arithmetic performance is still scarce, but even so, some studies have found a significant association between reading and writing numbers and mathematical performance (GEARY; HAMSON; HOARD, 2000; GEARY; HOARD; HAMSON, 1999). There is even evidence that, when compared to working memory capacity and non-symbolic numerical representations, knowledge of how to write the positional value of numbers, in children at the end of the first school year, is the best predictor of mathematical performance two years later (MOELLER et al., 2011).

An Australian study that evaluated 519 students in kindergarten and, soon after, in the 1st year, concerned with investigating the predictive skills of arithmetic performance, indicated that knowledge of numbers in Arabic format at the beginning of the school was important for the development of arithmetic skills later (MALONE; BURGOYNE; HULME, 2019). These findings are corroborated by a British study that also followed its 71 participants from kindergarten to 1st grade, which specifically investigated the relationship between Arabic numeral knowledge and arithmetic performance. In such a study, it was found that numerical knowledge at 4 years old, assessed by number transcoding ability, is a unique predictor of arithmetic ability at 6 years old (HABERMANN et al., 2020).

Another cognitive skill involved in initial numerical knowledge and indicated as important for mathematical performance is a number line estimation. To assess this ability, a task is commonly used in which participants must indicate the position of a number on a number line, which only has the markings of the initial and final number. Some studies suggest that the better the ability to perform estimates, the better the performance in standardized mathematics tests (BOOTH; SIEGLER, 2006), and that the performance in number line estimation progressively improves with increasing age and school year (LINK; NUERK; MOELLER, 2014; SASANGUIE; VAN DEN BUSSCHE; REYNVOET, 2012). In addition, there are already results indicating that the more accurate children are in locating numbers on the number line, the better their mathematical performance will be years later (ARAGÓN et al., 2019; GILMORE et al., 2018; SASANGUIE; VAN DEN BUSSCHE; REYNVOET, 2012).

The main evidence is that performance in number line estimation is related to basic numerical skills, such as categorization and comparison of numerical magnitudes, and complex arithmetic skills, such as calculations with the four fundamental operations (BOOTH; SIEGLER, 2006; 2008; LASKI; SIEGLER, 2007; LINK; NUERK; MOELLER, 2014; SIEGLER; BOOTH, 2004). In addition, number line estimation is an important resource for initial numerical representation and understanding, as it requires integration between conceptual numerical knowledge, such as familiarity with numbers, place value and numerical understanding, and numerical procedural knowledge, as the strategies used and proportional judgment (DACKERMANN et al., 2015; GILMORE et al., 2018; LASKI; SIEGLER, 2007; SIEGLER; THOMPSON; OPFER, 2009).

Starting from initial numerical knowledge, which involves understanding the numerical system, we move on to understanding the four fundamental operations (addition, subtraction, multiplication, and division). In this sense, the understanding of mathematical operations goes beyond simply the fact that the student can solve an algorithm. Understanding mathematical operations involves, firstly, knowing the relationships between them and, mainly, perceiving the relationships between the quantities involved so after that, it will be possible to operate with the numbers involved in the calculation, with the possibility of following other resolution strategies in addition to the pre-established algorithms (NUNES; BRYANT, 2015). This understanding of the relationships between quantities, whether they are increasing or decreasing, grouped, or shared, for example, is what is defined as quantitative reasoning (NUNES et al., 2016). Understanding the relationships between quantities will help in understanding early math and even arithmetic calculations.

Quantitative reasoning can be classified into additive and multiplicative reasoning, according to the relationships established between quantities (NUNES et al., 2016). Both are essential for understanding the four fundamental operations of mathematics and their relationships. From the moment the children coordinate the necessary schemes to solve mathematical problems, they will develop operational reasoning and will obtain better performance in mathematical tasks (NUNES et al., 2009). There is still little evidence from longitudinal studies that have investigated quantitative reasoning as a skill capable of predicting mathematical success in later years. The research by Nunes et al. (2007) stands out who investigated whether quantitative reasoning, measured at the beginning of school life, was a significant predictor of mathematical performance, assessed 16 months later by a standardized test. For this, 53 British children with a mean age ranging from 6 to 7.3 years old, according to the moment in which the evaluation was carried out, were followed. The results indicated quantitative reasoning as a significant and specific predictor of mathematical performance, even after controlling the level of intelligence and working memory capacity of these participants (NUNES et al., 2007). A longitudinal study also investigated whether the quantitative reasoning and arithmetic skills of 1680 British students were predictive of their later mathematical performance, assessed at 11 and 14 years old (NUNES et al., 2012). Their findings showed that quantitative reasoning has a unique contribution in predicting mathematical performance at both time points evaluated in addition to the effects of working memory, intelligence, and arithmetic skills.

More recently, a study carried out with 115 Chinese children evaluated in the 1st year and then in the 2nd year, also to investigate the contributions of quantitative reasoning, specifically the additive one, for later mathematical performance, indicated it as a substantially explanatory of mathematical performance, both for calculation skills and for problem-solving (CHING; NUNES, 2017). Based on this evidence, the importance of quantitative reasoning for mathematical learning is highlighted, as well as how fundamental the understanding of the relationships between quantities is for understanding the formal algorithms used in solving arithmetic calculations, as well as for better mathematical performance in general.

Thus, the influence of domain-specific cognitive skills on the development of mathematical learning is highlighted. Furthermore, it is highlighted that well-established initial numerical skills provide a more consistent mathematical understanding and, consequently, school success in this area.

Our study

In this article, research is presented that sought to identify the skills, among the proposals, that predict the arithmetic performance of children in the 3rd and 4th grades of elementary school. In other words, the objective is to verify the influence of general and specific domain predictors on the arithmetic performance of the same group of students evaluated at the beginning and end of the school year. For this, six important skills for arithmetic performance were selected: working memory, phonemic awareness, reading comprehension, number transcoding, number line estimation, and quantitative reasoning. As a hypothesis, we expected to find the influence of both general domain and specific domain skills for arithmetic performance, that is, that at least some of the assessed variables would independently contribute to the outcome variable, especially working memory, which is quite reported in the literature as a predictor, and quantitative reasoning, given the proximity of procedures to arithmetic.

Most research to date has focused on investigating the cognitive abilities of preschool and 1st-grade students. Thus, this study proposes the evaluation of the cognitive abilities of students with more time in school, in addition to verifying the relationship of measures such as reading comprehension and quantitative reasoning, which, in addition to requiring formal school teaching, are little explored as possible predictors of arithmetic performance. Thus, this study allows the identification of precursor skills of arithmetic performance of Brazilian students who have been inserted for a longer time in the school context.

Thus, student performance was assessed in selected cognitive skills to identify the unique contribution of each to later arithmetic performance. It should be mentioned that this study is part of a research project registered on Plataforma Brasil and approved by the Research Ethics Committee of the researchers' home university, under number 82570618.9.0000.5347. We will also describe the composition of the sample, the procedures, and the tasks selected to evaluate the proposed skills.

METHOD

This study was carried out quantitatively, gathering longitudinal data on student performance, which was evaluated in two moments during the same school year. For data analysis, adequate statistical tests were considered to respond to the objectives proposed in this study. Below, we will describe the data collection procedures, the selection of participants, and the evaluation instruments used.

Participants

The minimum number of participants to conduct the study was determined from a sample calculation, using the Winpepi software (v11.48), for a regression analysis, considering six predictors, with a coefficient of determination $R^2 = 0.90$, with power of 80%, significance level of 5% and considering a loss of 30% of participants. This resulted in the required minimum number of 98 children, a minimum number sufficient to carry out the intended statistical tests.

As for participation in the research, authorization was requested from the Municipal Department of Education to carry out the research in schools. An authorization term was also required from each participating school, as well as the signature of a participation term to the teacher responsible for each class. Those responsible for students interested in participating were required to sign an Informed Consent Term and, from participating students, an Informed Assent Term.

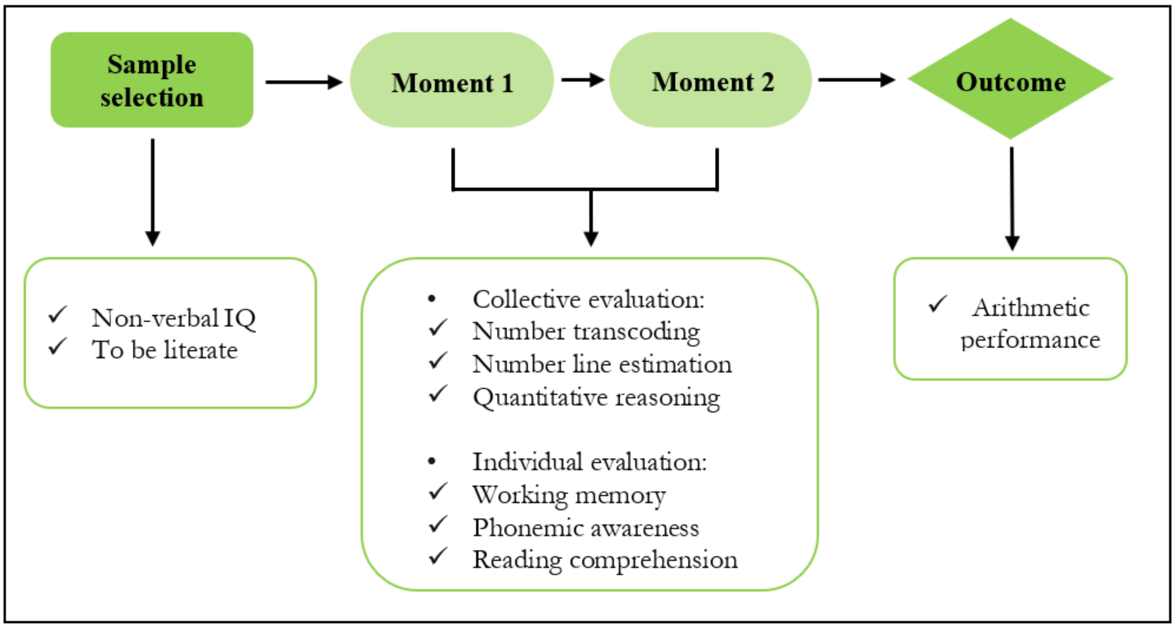
This research involved 127 children in the 3rd and 4th grades of elementary school from two municipal schools in the city of Porto Alegre (RS). Initially, the sample had 163 students, who performed all the previously described cognitive skills assessment activities (number transcoding, number line estimation, quantitative reasoning, working memory, phonemic awareness, and reading comprehension) and the assessment of the intellectual level. Two criteria were considered for the inclusion of participants in the sample: intellectual level and literacy. The intellectual level was measured based on the assessment of non-verbal reasoning, carried out using the Raven's Colored Progressive Matrices – Special Scale instrument (ANGELINI et al., 1999). The application of this measure intends to homogenize the sample, that is, to disregard children with the possibility of having an intellectual disability. Based on the test, the cutoff point was considered at the 25th percentile, which indicates the participant as being intellectually average. Below this percentile, the subject is classified as below average intellectual or with some intellectual disability (ANGELINI et al., 1999). Literacy was identified based on reading ability, considering literate only those participants who were able to complete the phonemic awareness and reading comprehension tasks. Thus, we have the result of a sample group of 127 students.

Data collection

The data collection process took place in 2018, having to start and end during the same school year to minimize losses of sample subjects. It was decided to carry out two evaluation moments, measuring the same skills in both, to verify a possible influence of the school on the development of these skills, as well as characterizing a longitudinal prediction study. The first moment of evaluation was carried out during April and May (beginning of the school year) and the second moment, in October and November (end of the school year), followed immediately by the evaluation of arithmetic performance (outcome variable). The flowchart below (Figure 1) summarizes the steps taken to collect data for this study.

Data collection consisted of the application of six tasks, one for each skill, plus the assessment of the student's intellectual level and arithmetic performance. During the evaluation in moments 1 and 2, the students participated in three sessions at each moment, two collective sessions, in which all students participated at the same time, and one individual, in which one student was evaluated at a time. In the first collective session of moment 1, the students' non-verbal reasoning was evaluated and, in the second collective session, number transcoding, number line estimation, and quantitative reasoning skills were evaluated, which were applied in sequence and in that order. All tasks were applied in the classroom, during the school shift, lasting approximately one hour for the first session and two hours to complete all tasks in the second session. In the third session of moment 1, which was done individually, working memory, phonemic awareness, and reading comprehension were evaluated, also during the school shift, but in a separate room and with an average duration of 30 minutes per participant.

Figure 1 – Research design



Source: our elaboration.

In moment 2, the sessions were configured as follows: first collective session, in which number transcoding, quantitative reasoning, and number line estimation were evaluated, following this order of application; second individual session, in which working memory, phonemic awareness, and reading comprehension were assessed; and the third collective session, to assess arithmetic performance. Below we describe the descriptions of the instruments used, following the same application order.

Instruments

Number transcoding evaluation task

In this task, participants are asked to write the numbers dictated to them. The task evaluates the number transcoding ability, consisting of 28 numbers from one to four digits, which must be written with their corresponding digits (LOPES-SILVA et al., 2014; 2016; MOURA et al., 2013). One point is assigned for each correct answer, totaling 28 points as a maximum score, and does not contain interruption criteria[2].

Number line estimation ability evaluation task

The number-position version was the number line estimation task used (SIEGLER; OPFER, 2003), which consists of asking the participant to mark the position of a number on a line delimited by the numbers 0 (on the left) and 100 (on the right). The 22 numbers to be estimated, taken from Laski and Siegler (2007), were randomly presented and the children had to mark their estimates in a notebook containing a number line and a number to be estimated on each page. This task has no stopping criteria. Performance was determined by calculating the accuracy that the students estimated each requested number, that is, by calculating the absolute error percentage (AEP) for each child. This calculation is adapted from Siegler and Booth (2004) and is done by dividing the difference, in absolute value, between the estimate made by the child and the number to be estimated, by the scale of the line. Better explaining: if a child is asked to estimate the number 40, but makes a mark corresponding to the number 30, the percentage of absolute error will be 10%. This value corresponds to the result of $|(30-40)/100|$. For analysis purposes, the numerical estimate variable was considered as "1 – AEP", that is, in the example above, the considered precision would be 90% (1 – 0.10 = 0.90). The maximum score in this task corresponds to 1 (100%), so the closer to this value, the more accurate the answer given by the child.

Quantitative reasoning evaluation task

The quantitative reasoning task, based on Nunes (2009), was applied to evaluate the ability to solve simple arithmetic problems, that is, involving only one mathematical operation and numbers up to 20. The quantitative relationships involved are additive reasoning, which includes situations of the composition of quantities, transformation, and comparison, and multiplicative reasoning, which contains situations of direct and inverse relationships between quantities and combinations. The task comprised 18 problems, 9 of additive reasoning and 9 of multiplicative reasoning. Each participant received a notebook containing only problem illustrations, with one problem per page, and no written information. The instructions were given orally by the evaluator, as it does not require the students' reading ability to understand the statement. The task has no stopping criteria. For the correction, the number of correct answers to the total number of questions was taken into account, which could reach 18 points as a maximum score.

Working memory evaluation task

The evaluation of working memory capacity was performed using the Battery of Working Memory Tests for Children (PICKERING; GATHERCOLE, 2001). From this material, the Memory of Blocks tasks were used, to evaluate the visuospatial component, and Memory of Digits in direct and inverse order, to evaluate the phonological and central executive components, respectively. Tasks are separated into levels, which progressively increase the amount of information to be remembered in each sequence. The test is stopped if the child makes three mistakes on the same level. Performance in this task is measured according to the number of correctly repeated sequences (PICKERING; GATHERCOLE, 2001), with a maximum score of 54 points for the tasks of Memory of Digits in Direct Order and Memory of Blocks and 36 points for the Digit memory task in reverse order.

[2] The interruption criteria refer to the moment the test ends, considering the number of consecutive errors by the evaluated student. In case the task does not present interruption criteria, it means that the test is done in its entirety, that is, the student can complete all the questions of the test without being interrupted due to mistakes made.

Phonemic awareness evaluation task

This task assesses the child's phonemic awareness through the suppression of phonemes, that is, the child hears a word and must say what the new word formed when a specified phoneme is excluded, for example: "*gavião*" without /g/ is "*avião*". The task consists of 28 words, which vary from 2 to 3 syllables and the phonemes to be suppressed are in different positions in the words. This task is accepted in research, having been applied previously and also in Brazilian samples (LOPES-SILVA et al., 2014; 2016). Its correction is determined by the total number of answers given correctly, reaching a maximum score of 28 points, and it has no interruption criteria.

Reading comprehension evaluation task

The task used in this study is the assessment of reading comprehension of expository texts, proposed by Saraiva, Moojen, and Munarski (2017), which is following the cognitive possibilities of students about concepts and knowledge about the subject read. For each school year, a different text was presented, respecting the expected cognitive abilities of each school level. The silent and oral reading of the text was requested, to then ask six questions related to the text: five with answers found in the text itself and one with an inferential answer. The score was determined by the number of answers given correctly, with a maximum of 12 points, and has no interruption criteria.

Arithmetic performance evaluation task

Arithmetic performance was assessed by the Arithmetic Subtest of the School Performance Test (SPT) (STEIN, 1994). The SPT is a standardized test for Brazilian reality and is widely used in research in Brazil to verify the school performance of elementary school children. This test comprises three subtests: arithmetic, reading, and writing. For this research, only the arithmetic subtest was used, which is composed of three simple problems presented orally and 35 arithmetic calculations presented in written form, with an increasing level of complexity. Children are asked to do as many questions as they can, with no time limit and no interruption criteria. Their score is determined by the total number of questions answered correctly, which can reach a maximum score of 38 points.

Data Analysis[3]

A quantitative analysis was carried out, using the R v.3.6.3 software, to verify the precursors of arithmetic performance among the assessed skills. For this, descriptive analyzes of the participants' performances in the tasks were carried out, considering the two evaluation moments: at the beginning and the end of the school year. Then, the Wilcoxon comparison test was conducted to verify the existence of a significant difference between the performances in these two evaluation moments. Conbrach's alpha coefficient (α) was also calculated to measure the internal consistency of the instruments used, considering the total number of questions in each task and the student's responses to each item.

After that, a Pearson linear correlation analysis was performed between the students' performances in each assessed skill. Afterward, a multiple linear regression analysis was performed to verify the predictive value of each of the measures in arithmetic performance. For such analyses, the performances in the first moment of evaluation were used, in which it is considered that the students received less influence from school teaching. Finally, mediation analysis was conducted to investigate the direct and indirect effects of predictive variables on arithmetic performance.

RESULTS

[3] The dataset that supports the results of this study is not publicly available, as they are still being analyzed for other derived studies. The request for access to the data can be made directly to the author, by e-mail (camila.nogues@ufrgs.br).

This study aimed to identify cognitive abilities as predictors of arithmetic performance in students in the 3rd and 4th grades of elementary school. For this, the performances of 127 students were analyzed. Table 1 shows the description of the sample, indicating the number of children by gender, by school year, and the average age.

Table 1 – Sample Categorization

		Total (%)	Mean (SD)	Minimum	Maximum
School grade	3rd	55 (4331)			
	4th	72 (56.69)			
Gender	F	79 (62.20)			
	M	48 (37.80)			
Age			9.3 (0.7)	8.2	11.3

Source: survey data.

The descriptive analyses, indicated in Table 2, show the student's performance in the tasks in both evaluation moments, at the beginning (moment 1) and at the end (moment 2) of the school year. In addition, the reliability of the tasks measured by Cronbach's alpha (α) is verified, which indicates that the higher the value of α, the more reliable the tasks are, that is, the more coherent the tasks are with what they propose to measure. Thus, the tasks had acceptable values and good reliability, allowing a more consistent interpretation of the results. The Wilcoxon comparison test was also performed to verify whether there was a significant improvement in student performance between the two evaluation times. The results of this comparison are indicated in the table by the p-value, which indicates the probability of significance of the result of the statistical test carried out, therefore, when this value is less than 5% (0.05), we have that the test result is significant. Thus, based on the p-value, the children's performance improved in all tasks at the end of the school year, confirming the hypothesis of a possible influence of school teaching on the development of these skills.

Table 2 – Descriptive analysis of the tasks evaluated in moments 1 and 2

		Moment 1		Moment 2		
	α*	Mean (SD)	Min. – Max.	Mean (SD)	Min. – Max.	p-value
WM – Phonological	0.89	25.81 (4.97)	16 – 42	26.56 (5.29)	16 – 48	**< 0.01**
WM – visuospatial	0.79	21.40 (3.98)	13 – 29	22.32 (4.09)	8 – 31	**< 0.05**
WM – Central Executive	0.84	9.26 (3.48)	1 – 21	10.22 (3.57)	5 – 22	**< 0.01**
Reading comprehension[1]	0.73 0.69	6.90 (2.63)	0 – 12	7.61 (2.58)	2 – 12	**< 0.05**
Phonemic awareness	0.90	19.53 (6.53)	1 – 28	21.27 (5.47)	5 – 28	**< 0.001**
Number transcoding	0.92	21.31 (5.73)	7 – 28	24.48 (4.33)	13 – 28	**< 0.001**
Number line estimation	0.90	0.89 (0.05)	0.69 – 0.97	0.91 (0.04)	0,77 – 0,97	**< 0.05**
Quantitative reasoning	0.72	8.24 (3.08)	0 – 16	10.28 (4.16)	0 – 18	**< 0.001**
Arithmetic Performance	--	--	--	13.17 (4.02)	2 – 23	--

* Cronbach's alpha coefficient (α): calculated based on the total number of questions in each task, it measures the reliability of the tasks and the internal consistency of the questions based on the participants' responses. Being values between 0.6 and 0.7, a questionable level, between 0.7 and 0.8, acceptable, between 0.8 and 0.9, a good level, and greater than 0.9, excellent.

[1]Note: In the Reading Comprehension task, the reliability coefficient was separated by school year, since the text and questions are different for each year. However, the other inferences are made based on the total sample.

Source: survey data.

Then, to understand the relationships between cognitive variables and arithmetic performance, a Pearson linear correlation analysis was performed between student performances on these measures, considering only the first evaluation moment (Table 3). This moment was chosen to conduct the other analyses for two reasons: first, because of the precedence in the evaluation time in the outcome variable, which characterizes the longitudinal study; second, because it was collected at the beginning of the school year, presenting less school interference than in the second evaluation moment, in which the children performed better in the evaluated tasks since they received school education throughout the school year.

Based on this analysis, we observed that performance in arithmetic presented a significant correlation with all assessed skills, in which the weakest was with the capacity of the central executive component of working memory (r=0.21, p<0.05) and the strongest with number transcoding (r=0.61, p<0.001). The correlation table also helps in the interpretation of the results of the regression analysis that will be reported later, because, in this way, it is possible to understand the variables that were not considered in the modeling process as those with a low correlation index.

Table 3 – Correlations between tasks evaluated at time 1 and arithmetic performance

	1	2	3	4	5	6	7	8
1. WM – PC	-							
2. WM – VC	-0.01	-						
3. WM – CE	0.29***	0.26**	-					
4. PA	0.26**	0.21*	0.39***	-				
5. RC	0.12	-0.03	0.27**	0.37***	-			
6. NT	0.35***	0.24**	0.28**	0.34***	0.24**	-		
7. NLE	0.12	0.28**	0.28**	0.31***	0.26**	0.43***	-	
8. QR	0.17	0.28**	0.33***	0.34***	0.40***	0.52***	0.36***	-
9. AP	0.23**	0.30***	0.21*	0.38***	0.23**	0.61***	0.32***	0.50***

*p<0.05; **p<0.01; ***p<0.001

Legend: 1. WM – PC: Phonological Component of Working Memory; 2. WM – VC: Visuospatial Component of Working Memory; 3. WM – CE: Central Executive Component of Working Memory; 4. PA: Phonemic Awareness; 5. RC: Reading Comprehension; 6. NT: Number Transcoding; 7. NLE: Number Line Estimation; 8. QR: Quantitative Reasoning; 9. AP: Arithmetic Performance.

Source: survey data.

After that, a multiple linear regression analysis was conducted. First, all variables were placed in the model at the same time, considering arithmetic performance as the outcome variable. The results can be seen in Table 4. The school grade and age variables were not included in the model because they are not variables of interest since the objective is to specifically identify cognitive abilities as predictors. It is also worth mentioning that the variable Working Memory was generated and calculated from the average of the total score (number of correct attempts) in each of the three components of working memory. This decision was taken based on the correlation indices of each of these components with arithmetic performance, which indicates a significant but weak correlation between the variables (phonological component: r=0.23, p<0.01; component visuospatial: r=0.30, p<0.001; central executive component: r=0.21, p<0.001). It is known that working memory is usually an important measure of mathematical performance, so it was verified whether the variable composed of the three components presents a higher correlation index with arithmetic performance. Then, from that, it was observed that the correlation index increased to a moderate correlation (r=0.37, p<0.001), which could favor the inclusion of this variable in the regression model.

From this first regression model, which explained 40.9% of the arithmetic performance (F(7,119)=13.46, p<0.001), the variables number transcoding (β=0.31, p<0.001) and reasoning quantitative (β=0.28, p<0.05) were the only ones indicated as predictors of the outcome variable.

Table 4 – Multiple Linear Regression Model 1

	Arithmetic Performance		
Predictive Variables	B	CI	p-value
Raven	-0.00	-0.15 – 0.15	0.761
Working Memory	0.05	-0.18 – 0.29	0.996

Phonemic Awareness	0.09	-0.00 – 0.19	0.062
Reading Comprehension	-0.04	-0.27 – 0.20	0.762
Number Line Estimation	0.18	-12.18 – 12.55	0.977
Number Transcoding	0.31	0.19 – 0.43	**<0.001**
Quantitative Reasoning	0.28	0.04 – 0.51	**0.021**

R^2 adjusted = 0.409, F(7,119) = 13.46, p<0.001
Source: survey data.

In searching for a more adequate model, the stepwise forward method of variable selection was performed, in which each variable is added to the model separately, one after the other, considering the decreasing order of influence. The statistical analysis program identifies the variables to be added to the final model according to their influence and stops modeling when no other added variable presents a significant value. Therefore, six variables were considered as possible predictors: working memory, phonemic awareness, reading comprehension, number transcoding, number line estimation, and quantitative reasoning. Thus, following the steps of the chosen regression method, in the resulting model, three predictors for the arithmetic performance were indicated. First, the number transcoding variable was added, then the quantitative reasoning variable, and finally, the phonemic awareness variable, as shown in Table 5. This model explains 42.7% of the variance in arithmetic performance (F(3.123)=32.27, p<0.001), the other measures did not show a significant effect to be included in the model and help explain the arithmetic performance.

Table 5 – Model 2 and final of Multiple Linear Regression

	Arithmetic Performance				
Predictive Variables	R^2 partial	ΔR^2	B	CI	p-value
Number Transcoding	0.371	0.371	0.32	0.21 – 0.43	**<0.001**
Quantitative Reasoning	0.410	0.039	0.27	0.06 – 0.48	**0.003**
Phonemic Awareness	0.427	0.017	0.10	0.01 – 0.19	**0.034**

Final model: R^2 adjusted = 0.427, F(3,123)=32.27, p<0.001
Source: survey data.

Based on these results, we found that only three variables appeared as predictors of arithmetic performance and number transcoding was the one with the greatest influence (β=0.32, p<0.001). It is also possible to observe, according to the resulting model, that this same variable alone explains 37.1% of the variance in arithmetic performance, while quantitative reasoning contributes an additional 3.9% and phonemic awareness adds 1.7% in explaining students' arithmetic performance.

To get a complete idea of how these variables influence arithmetic performance, a mediation analysis was conducted. This type of analysis helps us to identify whether an intermediate variable is also involved in the relationship between one of the predictor variables and the response variable. Therefore, for this purpose, the mediator variable was the one with the highest influence value (regression coefficient, β) in the model shown in Table 5, which corresponds to the number transcoding measure (β=0.32, p<0.001). Also, the influence of quantitative reasoning and phonemic awareness measures increases when the effect of number transcoding is controlled, as can be seen in Table 6.

Table 6 – Regression model without the influence of the number transcoding variable on the outcome

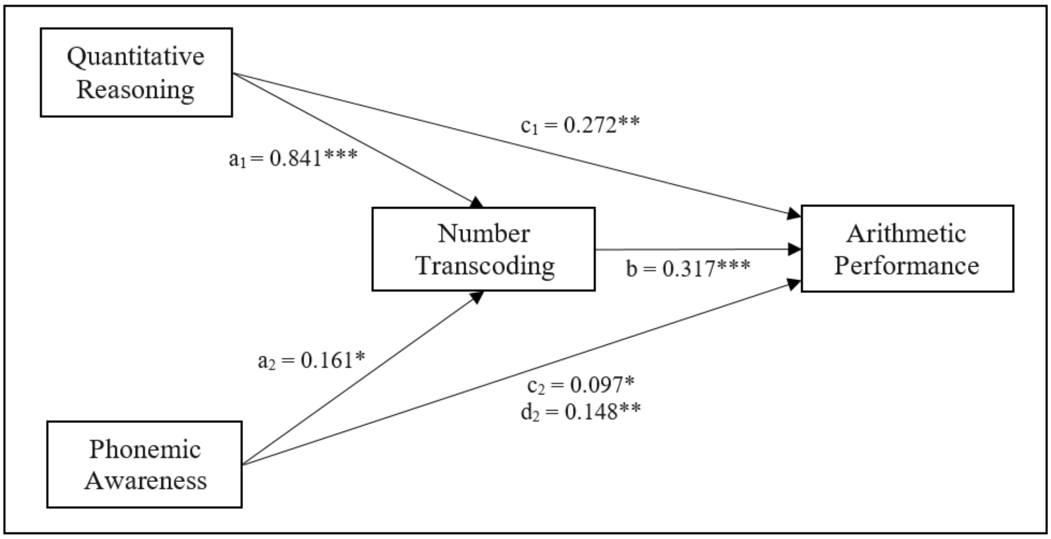
	Arithmetic Performance		
Predictors	B	CI	p-value
Quantitative Reasoning	0.54	0.05 – 0.25	**<0.001**
Phonemic Awareness	0.15	0.33 – 0.75	**0.003**

Final model: R^2 ajusted = 0.285, $F(2,124) = 26.13$, $p<0.001$
Source: survey data.

Then, the mediation analysis model was conducted, in which the direct (c1 and c2) and indirect effects (a1b and a2b) were estimated for the predictive variables of quantitative reasoning and phonemic awareness, respectively, through number transcoding, which was considered as an intermediate variable. The direct and indirect effects of each measure, when added together, are equivalent to the total effect of each of the independent variables, quantitative reasoning, and phonemic awareness, on the outcome variable, arithmetic performance.

As can be seen in Figure 2, when first analyzing the mediation relationship between quantitative reasoning and arithmetic performance through number transcoding, it appears that direct significant effects were found (c1=0.272, SE=0.103, p<0.001) and indirect (a1b=0.267, SE=0.066, p<0.001) between quantitative reasoning and arithmetic. This indicates that number transcoding is a partial mediator of the relationship between the other two measures since a part of the total effect (d1=0.539, SE=0.103, p<0.01) is also explained by the direct effect between quantitative reasoning and arithmetic. To better explain, although a higher performance in quantitative reasoning is related to a higher score in arithmetic, the effect of this relationship is reduced by almost half (49.5%) when the number transcoding ability is also considered.

Figure 2 – Mediation Model



*p<0.05; **p<0.01; ***p<0.001
Source: survey data.

Then, the mediation effect was also verified by inserting the phonemic awareness variable and keeping number transcoding as the mediating variable. The results suggest significant direct (c2=0.097, SE=0.044, p<0.05) and indirect (a2b=0.051, SE=0.024, p<0.05) effects. Therefore, number transcoding also explained a part of the total effect (d2=0.148, SE=0.049, p<0.01) between phonemic awareness and arithmetic. The indirect effect of phonemic awareness on arithmetic performance is greater than the direct effect, that is, its effect on arithmetic is more relevant when mediated by number transcoding.

Thus, the results indicate that the variables of quantitative reasoning and phonemic awareness are explanatory of arithmetic performance and present effects mediated by number transcoding. The results suggest a possible way to try to elucidate the importance of phonemic awareness for arithmetic performance. Thus, the analysis of this study can be synthesized in a final model of structural equations, from which it can be concluded that the three predictors for arithmetic performance had significant indirect and direct effects, which supports their relevance for the development of reasoning arithmetic.

FINAL CONSIDERATIONS

This article shows research carried out with students in the 3rd and 4th grades of elementary school, which aimed to identify cognitive skills as predictors of arithmetic performance, that is, to verify the existence of a causal relationship between some cognitive skills, general, specific, and arithmetic domains. Based on the literature, some skills were selected to test the hypothesis that they are predictors of arithmetic performance in already literate students. Of the different skills indicated, this study focused on working memory skills, phonemic awareness, reading comprehension, number transcoding, number line estimation, and quantitative reasoning. To achieve the objective, students were evaluated at two moments throughout the school year, at the beginning and the end; however, only the moment evaluated at the beginning of the school year was considered to avoid the effect of school learning during this period.

The main results of this study show that the significant predictors of arithmetic performance were phonemic awareness as a general domain skill and number transcoding and quantitative reasoning, among the domain of specific skills. This is in line with previous evidence indicating the importance of number identification, including reading, and writing numbers, for learning arithmetic. Also, phonemic awareness, which is part of phonological processing, is highlighted as a predictor of general mathematical performance, especially in arithmetic calculations (HECHT et al., 2001; SIMMONS; SINGLETON; HORNE, 2008). The regression model also confirms the hypothesis that quantitative reasoning significantly contributes to arithmetic ability. We might think that understanding the relationship between quantities and between operations is necessary to decide which procedure to follow and apply it correctly. Therefore, quantitative reasoning is of importance before learning algorithms for solving mathematical operations. More specifically, arithmetic is not just about memorizing basic facts, but also about understanding the relationships between numbers to solve mathematical tasks, which assumes understanding the numerical system and the specific characteristics that compose it (CHING; NUNES, 2017). In this sense, from the understanding of numbers and the numerical system, quantitative reasoning will contribute to arithmetic knowledge. Based on this, it will also be possible to develop more effective solution strategies, since the calculation process requires a more detailed understanding of the number and relationships between operations. In this way, understanding these relationships will form the basis for the development of more advanced calculation strategies that will help children to turn complex problems into simpler ways to solve them (CHING; NUNES, 2017).

Based on the findings, it is also worth noting that working memory did not appear as a predictor of arithmetic performance in 3rd and 4th-grade students. This result differs from previous research that indicates this ability as an explanation of mathematical performance throughout the early years of elementary school. First, it is pertinent to consider the diversity of existing tasks to assess working memory capacity, which can lead to divergent results between studies due to the choice of task used. However, when trying to elucidate this non-significant result of the influence of working memory on arithmetic performance, some reasons are raised. A possible explanation is that a greater demand for working memory is linked to the complexity of the evaluated mathematical task. In this sense, the test used in this study to evaluate the students' arithmetic performance only requested the resolution of calculations with operations, which many students were already used to solving in the classroom, therefore, the task may not have demanded so much memory. of students' work. It is also important to point out that students left blank calculations with operations not yet learned at school. This fact may be due to the way mathematics is taught in schools, which prioritizes the understanding of a sequence of steps to be followed to solve a given algorithm and, often, just one way to arrive at the result. So, when the student is faced with an algorithm whose resolution procedure he does not know, he ends up giving up thinking about a strategy to solve it, thus not including a greater demand on the working memory to organize the information and elaborate a solution strategy. Another possible explanation is that according to the student's cognitive maturation, that is, the development of knowledge, and the advancement in the school years, less demand on working memory is required for procedures already learned.

It is also possible that the fact that the other variables do not appear as predictors of arithmetic performance is due to the task considered for evaluating the outcome, which required little reading and elaboration of resolution strategies. Despite this, reading comprehension and number line estimation skills correlated, even if at a weak level, with arithmetic performance, indicating that they are important skills for this learning, although they do not exert an explanatory influence on such performance. However, the purpose of this study was to evaluate the prediction from a standardized test, which only measures the ability in arithmetic calculations. Thus, other tasks that assess more comprehensive mathematical knowledge may be necessary to identify the prediction of these skills in already literate students in the Brazilian context.

When analyzing the findings of this study in more detail, a point that deserves attention is the fact that number transcoding was the measure with the highest explanatory value of arithmetic performance. From the analyses, when it is removed from the model, the predictive value of the other variables increases. Thus, the number transcoding may be sharing this explanatory effect. Therefore, a mediation analysis was conducted, confirming that it is an intermediate measure of the effect of quantitative reasoning and phonemic awareness on arithmetic performance.

This fact also shows why phonemic awareness, or more broadly phonological awareness, is involved in arithmetic. Studies indicate this cognitive ability is important for performance in mathematics (HECHT et al., 2001; SIMMONS; SINGLETON; HORNE, 2008; LOPES-SILVA et al., 2014; 2016), but little is discussed as to why this ability establishes a causal relationship with arithmetic. Therefore, the findings of this study help clarify this by showing that the relationship between phonemic and arithmetic awareness is more explanatory when mediated by number transcoding. This can be explained by the fact that phonemic awareness involves different cognitive resources, more than just being responsible for the quality of phonological coding (SIMMONS; SINGLETON; HORNE, 2008). This skill also involves retaining phonological information in short-term memory, while this information is processed through central executive resources (HECHT et al., 2001; SIMMONS; SINGLETON; HORNE, 2008). This is also necessary when representing numbers since the identification of multidigit symbols explicitly requires the transcoding of the spoken number, in verbal form, to the format written in numbers (HABERMANN et al., 2020). In this sense, the evidence reported here converges with previous studies that also indicate number transcoding and phonemic awareness as predictors of arithmetic performance. Moreover, the results described go beyond previous studies, indicating number transcoding as a mediator of the causal relationship between phonemic and arithmetic awareness.

Some limitations must be considered. Data were collected in the same school year, which prevented us from investigating whether these skills are also related to individual changes in students' arithmetic learning over time and whether these skills remain predictors in later school years. However, this was an exploratory study and, therefore, these results can be confirmed through future research, preferably longitudinal, which can follow the arithmetic performance of students over the school years and verify the cognitive skills that remain with influence in this learning. In addition, it is important to consider mathematical performance more broadly, assessing students' knowledge in other domains such as problem-solving, geometry, algebra, etc., since the assessed task interferes with the cognitive skills that will be required for its resolution.

Thus, we concluded that basic abilities to identify numbers and their representation through numbers are determining factors for better arithmetic learning since knowing how to write a number requires knowledge of the numerical system. Furthermore, it is important to understand the relationship between quantities and between operations to understand the procedure to follow in an algorithm. Betting on the development of these skills, from the beginning of school, enables significant gains in arithmetic performance in later years. In this study, basic skills like these proved to be important also in the final phase of the initial years of elementary school, which makes it possible to infer that developing such skills from the first school year also allows the prevention of mathematical difficulties that may eventually arise.

When thinking about teaching and learning mathematics at school, a common idea among teachers and education professionals is that students first need to be taught how to formally solve arithmetic calculations and then deal with various types of mathematical problems. Therefore, students are taught to reason about relationships after learning to solve algorithms. However, the results showed that quantitative reasoning, that is, understanding the relationships between quantities, is the cause of better performance in arithmetic. Thus, the suggestion is to avoid the predominance of learning by procedures, which are often presented without connection with everyday situations, and encourage children to discuss the proposed problems and the relationships involved between quantities. In addition, propose tasks that develop the understanding of the numerical system and the recognition of numbers in their Arabic and verbal formats.

Therefore, the evidence reported here points to the importance of numerical skills in the development of arithmetic comprehension in Brazilian students. This study also contributes to a broader understanding of the cognitive processes involved in arithmetic learning. From this, we highlight that the understanding of the numerical system, as well as the conceptual understanding of arithmetic are fundamental for the development of procedural arithmetic.

REFERENCES

ANDERSSON, Ulf. Working memory as a predictor of written arithmetical skills in children: The importance of central executive functions. *British Journal of Educational Psychology*, Wiley Online Library: Hoboken, EUA, v. 78, n. 2, p. 181–203, 2008. <https://doi.org/10.1348/000709907X209854>.

ANGELINI, Arrigo L. *et al*. *Matrizes Progressivas Coloridas de Raven: Escala Especial*. São Paulo: CETEPP, 1999.

ARAGÓN, Estíbaliz *et al*. Individual differences in general and specific cognitive precursors in early mathematical learning. *Psicothema*, Astúrias, Espanha, v. 31, n. 2, p. 156–162, 2019. <https://doi.org/10.7334/psicothema2018.306>.

BADDELEY, Alan. The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, v. 4, n. 11, p. 417–423, 2000.

BADDELEY, Alan. Memória de Trabalho. *In*: BADDELEY, A.; ANDERSON, M. C.; EYSENCK, M. W. (org.). *Memória*. Artmed: Porto Alegre, 2011.

BADDELEY, Alan. D.; HITCH, Graham. Working Memory. *In*: BOWER, G. H. B. T. (org.). *The psychology of learning and motivation: Advances in research and theory*. Academic Press: Nova Iorque, 1974. v. 8p. 47–89. <https://doi.org/10.1016/S1364-6613(00)01538-2>.

BOOTH, Julie L.; SIEGLER, Robert S. Developmental and individual differences in pure numerical estimation. *Developmental Psychology*, APA: Washinton, EUA, v. 42, n. 1, p. 189–201, 2006. <https://doi.org/10.1037/0012-1649.41.6.189>.

BOOTH, Julie L.; SIEGLER, Robert S. Numerical Magnitude Representations Influence Arithmetic Learning. *Child Development*, Wiley Online Library: Hoboken, EUA, v. 79, n. 4, p. 1016–1031, 2008. <https://doi.org/10.1111/j.1467-8624.2008.01173.x>.

BRASIL. *Base Nacional Comum (BNCC)*. MEC, Brasília, p. 600, 2018.

BULL, Rebecca; ESPY, Kimberly A.; WIEBE, Sandra A. Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, Taylor & Francis Group: Abingdon, Reino Unido, v. 33, n. 3, p. 205–228, 2008. <https://doi.org/10.1080/87565640801982312>.

CANÁRIO, Nádia; NUNES, Maria Vânia S. Buffer Episódico 10 anos depois: revisão de um conceito. *Revista Neurociências*, 20(2), 311–319, 2012. <https://doi.org/10.34024/rnc.2012.v20.8282>.

CARR, Martha *et al.* A longitudinal study of spatial skills and number sense development in elementary school children. *Journal of Educational Psychology*, APA: Washington, EUA, v. 112, n. 1, p. 53–69, 2020. <https://doi.org/10.1037/edu0000363>.

CASEY, Beth M. *et al.* Girls' Spatial Skills and Arithmetic Strategies in First Grade as Predictors of Fifth-Grade Analytical Math Reasoning. *Journal of Cognition and Development*, Taylor & Francis Group: Abingdon, Reino Unido, v. 18, n. 5, p. 530–555, 2017. <https://doi.org/10.1080/15248372.2017.1363044>.

CHING, Boby H.-H.; NUNES, Terezinha. The Importance of Additive Reasoning in Children's Mathematical Achievement: A Longitudinal Study. *Journal of Educational Psychology*, APA: Washington, EUA, v. 190, n. 4, p. 477-508, 2017. <http://dx.doi.org/10.1037/edu0000154>.

CHU, Felicia W.; VANMARLE, Kristy; GEARY, David C. Predicting children's reading and mathematics achievement from early quantitative knowledge and domain-general cognitive abilities. *Frontiers in Psychology*, Frontiers: Lausanne, Suíça, v. 7, n. 775, p. 1–14, 2016. <https://doi.org/10.3389/fpsyg.2016.00775>.

DACKERMANN, Tanja *et al.* An integration of competing accounts on children's number line estimation. *Frontiers in Psychology*, Frontiers: Lausanne, Suíça, v. 6, n. 884, p. 1–7, 2015. <https://doi.org/10.3389/fpsyg.2015.00884>.

DECKER, Scott. L.; ROBERTS, Alycia M. Specific cognitive predictors of early math problem solving. *Psychology in the Schools*, Wiley Online Library: Hoboken, EUA, v. 52, n. 5, p. 477–488, 2015. <https://doi.org/10.1002/pits.21837>.

DESOETE, Annemie *et al.* Classification, Seriation, and Counting in Grades 1, 2, and 3 as Two-Year Longitudinal Predictors for Low Achieving in Numerical Facility and Arithmetical Achievement? *Journal of Psychoeducational Assessment*, SAGE Publications: Thousand Oaks, EUA, v. 27, n. 3, p. 252–264, 2009. <https://doi.org/10.1177/0734282908330588>.

FUCHS, L. S. *et al.* The cognitive correlates of third-grade skill in arithmetic, algorithmic computation, and arithmetic word problems. *Journal of Educational Psychology*, APA: Washington, EUA, v. 98, n. 1, p. 29–43, 2006. <doi.org/10.1037/0022-0663.98.1.29>.

FUHS, Mary W.; HORNBURG, Caroline B.; MCNEIL, Nicole M. Specific early number skills mediate the association between executive functioning skills and mathematics achievement. *Developmental Psychology*, APA: Washington, EUA, v. 52, n. 8, p. 1217–1235, 2016. <https://doi.org/10.1037/dev0000145>.

GATHERCOLE, Susan E. Cognitive Psychology of Memory. *In*: BYRNE, J. H. *et al.* (Eds.) *Learning and Memory: A Comprehensive Reference*, 1 ed., v. 2, Amsterdã: Elsevier, 2008, p. 33–51.

GEARY, David C. Cognitive predictors of achievement growth in mathematics: A 5-year longitudinal study. *Developmental Psychology*, APA: Washington, EUA, v. 47, n. 6, p. 1539–1552, 2011. <https://doi.org/10.1037/a0025510>.

GEARY, David C.; HAMSON, Carmen O.; HOARD, Mary K. Numerical and Arithmetical Cognition: A Longitudinal Study of Process and Concept Deficits in Children with Learning Disability. *Journal of Experimental Child Psychology*, Elsevier: Amsterdã, Holanda, v. 77, n. 3, p. 236–263, 2000. <https://doi.org/10.1006/jecp.2000.2561>.

GEARY, David C.; HOARD, Mary K.; HAMSON, Carmen O. Numerical and Arithmetical Cognition: Patterns of Functions and Deficits in Children at Risk for a Mathematical Disability. *Journal of Experimental Child Psychology*, Elsevier: Amsterdã, Holanda, v. 74, n. 3, p. 213–239, 1999. <https://doi.org/10.1006/jecp.1999.2515>.

GILLON, Gail T. *Phonological Awareness:* from research to practice. 2 ed. Nova Iorque: Guilford Publications, 2017.

GILMORE, Camilla *et al.* Understanding arithmetic concepts: The role of domain-specific and domain-general skills. *PLoS ONE*, PLOS: São Francisco, EUA, v. 13, n. 9, p. 1–20, 2018. <https://doi.org/10.1371/journal.pone.0201724>.

HABERMANN, Stefanie *et al.* The critical role of Arabic numeral knowledge as a longitudinal predictor of arithmetic development. *Journal of Experimental Child Psychology*, Elsevier: Amsterdã, Holanda, v. 193, n. 2020, p. 104794, 2020. <https://doi.org/10.1016/j.jecp.2019.104794>.

HAWES, Zachary *et al.* Relations between numerical, spatial, and executive function skills and mathematics achievement: A latent-variable approach. *Cognitive Psychology*, Elsevier: Amsterdã, Holanda, v. 109, n. dez. 2018, p. 68–90, 2019. <https://doi.org/10.1016/j.cogpsych.2018.12.002>.

HECHT, Steven A. *et al.* The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: A longitudinal study from second to fifth grades. *Journal of Experimental Child Psychology*, Elsevier: Amsterdã, Holanda, v. 79, n. 2, p. 192–227, 2001. <https://doi.org/10.1006/jecp.2000.2586>.

KISS, Alysson J.; NELSON, Gena; CHRIST, Theodore. J. Predicting Third-Grade Mathematics Achievement: A Longitudinal Investigation of the Role of Early Numeracy Skills. *Learning Disability Quarterly*, SAGE Publications: Thousand Oaks, EUA, v. 42, n. 3, p. 161–174, 2019. <https://doi.org/10.1177/0731948718823083>.

KRAJEWSKI, Kristin; SCHNEIDER, Wolfgang. Early development of quantity to number-word linkage as a precursor of mathematical school achievement and mathematical difficulties: Findings from a four-year longitudinal study. *Learning and Instruction*, Elsevier: Amsterdã, Holanda, v. 19, n. 6, p. 513–526, 2009. <https://doi.org/10.1016/j.learninstruc.2008.10.002>.

LASKI, Elida V.; SIEGLER, Robert S. Is 27 a big number? correlational and causal connections among numerical categorization, number line estimation, and numerical magnitude comparison. *Child Development*, Wiley Online Library: Hoboken, EUA, v. 78, n. 6, p. 1723–1743, 2007. <https://doi.org/10.1111/j.1467-8624.2007.01087.x>.

LINK, Tanja; NUERK, Hans C.; MOELLER, Korbinian. On the relation between the mental number line and arithmetic competencies. *Quarterly Journal of Experimental Psychology*, SAGE Publications: Thousand Oaks, EUA, v. 67, n. 8, p. 1597–1613, 2014. <http://dx.doi.org/10.1080/17470218.2014.892517>.

LOPES-SILVA, Júlia B. *et al.* Phonemic awareness as a pathway to number transcoding. *Frontiers in Psychology*, Frontiers: Lausanne, Suíça, v. 5, n. jan., p. 1–9, 2014.

<https://doi.org/10.3389/fpsyg.2014.00013>.

LOPES-SILVA, Júlia B. *et al.* What Is Specific and What Is Shared Between Numbers and Words? *Frontiers in Psychology*, Frontiers: Lausanne, Suíça, v. 7, n. fev., p. 1–9, 2016. <https://doi.org/10.3389/fpsyg.2016.00022>.

MALONE, Stephanie A.; BURGOYNE, Kelly; HULME, Charles. Number knowledge and the approximate number system are two critical foundations for early arithmetic development. *Journal of Educational Psychology*, APA: Washington, EUA, n. out., 2019. <https://doi.org/10.1037/edu0000426>.

MOELLER, Korbinian *et al.* Early place-value understanding as a precursor for later arithmetic performance—A longitudinal study on numerical development. *Research in Developmental Disabilities*, Elsevier: Amsterdã, Holanda, v. 32, n. 5, p. 1837–1851, 2011. <https://doi.org/10.1016/j.ridd.2011.03.012>.

MOURA, Ricardo *et al.* Transcoding abilities in typical and atypical mathematics achievers: The role of working memory and procedural and lexical competencies. *Journal of Experimental Child Psychology*, Elsevier: Amsterdã, Holanda, v. 116, n. 3, p. 707–727, 2013. <http://dx.doi.org/10.1016/j.jecp.2013.07.008>.

MOURA, Ricardo *et al.* From "Five" to 5 for 5 Minutes: Arabic Number Transcoding as a Short, Specific, and Sensitive Screening Tool for Mathematics Learning Difficulties. *Archives of Clinical Neuropsychology*, Oxford University Press: Oxford, Inglaterra, v. 30, n. 1, p. 88–98, 2015. <https://doi.org/10.1093/arclin/acu071>.

NOBRE, Alexandre de P. *et al.* Tasks for assessment of the episodic buffer: a systematic review. *Psychology & Neuroscience*, 6(3), 331–343, 2013. <https://doi.org/10.3922/j.psns.2013.3.10>.

NOGUES, Camila P.; DORNELES, Beatriz V. Systematic review on the precursors of initial mathematical performance. *International Journal of Educational Research Open,* Elsevier: Amsterdã, Holanda, v. 2, n. 2(January), p. 1–17, 2021. <https://doi.org/10.1016/j.ijedro.2021.100035>.

NUNES, Terezinha. *Teacher notes*. Family-School Partnership to Promote Mathematics for Deaf Children. Oxford: Universidade de Oxford, Departamento de Educação, 2009.

NUNES, Terezinha; BRYANT, Peter. The Development of Mathematical Reasoning. In: Lerner, Richard M. (Ed.), *Handbook of Child Psychology and Developmental Science*, 7 ed., Wiley: Hoboken, EUA, p. 1–48, 2015. <https://doi.org/10.1002/9781118963418.childpsy217>.

NUNES, Terezinha *et al.* The contribution of logical reasoning to the learning of mathematics in primary school. *British Journal of Developmental Psychology*, Wiley: Hoboken, EUA, v. 25, n. 1, p. 147–166, 2007. <https://doi.org/ 10.1348/026151006X153127>.

NUNES, Terezinha *et al. Educação matemática:* números e operações numéricas. Volume 1. 2 ed. São Paulo: Cortez, 2009.

NUNES, Terezinha *et al.* The Relative Importance of Two Different Mathematical Abilities to Mathematical Achievement. *British Journal of Educational Psychology*, Wiley Online Library: Hoboken, EUA*,* v. 82*,* n. 1, p. 136-156, 2012. <https://doi.org/10.1111/j.2044-8279.2011.02033.x>.

NUNES, Terezinha *et al.* Teaching and Learning About Whole Numbers in Primary School. *In*: *ICME-13 Topical Surveys*. Springer: Hamburg, Alemanha, 2016. <https://doi.org/10.1007/978-3-319-45113-8>.

PASSOLUNGHI, Maria Chiara; LANFRANCHI, Silvia. Domain-specific and domain-general precursors of mathematical achievement: A longitudinal study from kindergarten to first grade. *British Journal of Educational Psychology*, Wiley Online Library: Hoboken, EUA, v. 82, n. 1, p. 42–63, 2012. <https://doi.org/10.1111/j.2044-8279.2011.02039.x>.

PASSOLUNGHI, Maria Chiara; VERCELLONI, Barbara; SCHADEE, Hans. The precursors of mathematics learning: Working memory, phonological ability and numerical competence. *Cognitive Development*, Elsevier: Amsterdã, Holanda, v. 22, n. 2, p. 165–184, 2007. <https://doi.org/10.1016/j.cogdev.2006.09.001>.

PICKERING, Susan J.; GATHERCOLE, Susan E. *Working Memory Test Battery for Children (WMTB-C).* London: Psychological Corporation, 2001.

SARAIVA, Rosália A.; MOOJEN, Sônia; MUNARSKI, Roberta. *Avaliação da compreensão leitora de textos expositivos: para fonoaudiólogos e psicopedagogos*, 3. ed., São Paulo: Casa do Psicólogo, 2017.

SASANGUIE, Delphine; VAN DEN BUSSCHE, Eva; REYNVOET, Bert. Predictors for Mathematics Achievement? Evidence from a Longitudinal Study. *Mind, Brain, and Education*, Wiley Online Library: Hoboken, EUA, v. 6, n. 3, p. 119-128, 2012. <https://doi.org/10.1111/j.1751-228X.2012.01147.x>.

SIEGLER, Robert; BOOTH, Julie. Development of numerical estimation in young children. *Child development*, Wiley Online Library: Hoboken, EUA, v. 75, n. 2, p. 428–44, 2004. <https://doi.org/10.1111/j.1467-8624.2004.00684.x>.

SIEGLER, Robert S.; OPFER, J. The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science*, SAGE Publications: Thousand Oaks, EUA, v. 14, n. 3, p. 237–243, 2003.

SIEGLER, R. S.; THOMPSON, C. A.; OPFER, John E. The logarithmic-to-linear shift: One learning sequence, many tasks, many time scales. *Mind, Brain, and Education*, Wiley Online Library: Hoboken, EUA, v. 3, n. 3, p. 143–150, 2009. <https://doi.org/10.1111/1467-9280.02438>.

SIMMONS, Fiona; SINGLETON, Chris; HORNE, Joanna. Brief report - Phonological awareness and visual-spatial sketchpad functioning predict early arithmetic attainment: Evidence from a longitudinal study. *European Journal of Cognitive Psychology*, Taylor & Francis Group: Abingdon, Reino Unido, v. 20, n. 4, p. 711–722, 2008. <https://doi.org/10.1080/09541440701614922>.

SOARES, Magda. *Alfabetização:* a questão dos métodos. São Paulo: Contexto, 2019.

STEIN, Lilian. *Teste de Desempenho Escolar: manual para a aplicação e interpretação*. São Paulo: Casa do Psicólogo, 1994.

WONG, Terry T.-Y.; HO, Connie S.-H. Component Processes in Arithmetic Word-Problem Solving and Their Correlates. *Journal of Educational Psychology*, APA: Washinton, EUA, v. 109, n. 4, p. 520-531, 2017. <http://dx.doi.org/10.1037/edu0000149>.

XENIDOU-DERVOU, Iro *et al.* Cognitive predictors of children's development in mathematics achievement: A latent growth modeling approach. *Developmental Science*, Wiley Online Library: Hoboken, EUA, v. 21, n. 6, p. 1–14, 2018. <https://doi.org/10.1111/desc.12671>.

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Author 3 – Data collection and final writing review.
Author 4 – Coordinator of the project and revision of the final writing.

CONFLICT OF INTEREST DECLARATION

The authors declare that there is no conflict of interest with this article.