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Examining the relevance of basic numerical skills for mathematical achievement in secondary school using a within-task assessment approach

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ABSTRACT

Previous research repeatedly found basic numerical abilities (e.g., magnitude understanding, arithmetic fact knowledge, etc.) to predict young students' current and later arithmetic achievement as assessed by achievement tests – even when controlling for the influence of domain-general abilities (e.g., intelligence, working memory). However, to the best of our knowledge, previous studies hardly addressed this issue in secondary school students. Additionally, they primarily assessed basic numerical abilities in a between-task approach (i.e., using different tasks for different abilities). Finally, their relevance for real-life academic outcomes such as mathematics grades has only rarely been investigated. The present study therefore pursued an approach using one and the same task (i.e., a within-task approach) to reduce confounding effects driven by between-task differences. In particular, we evaluated the relevance of i) number magnitude understanding, ii) arithmetic fact knowledge, and iii) conceptual and procedural knowledge for the mathematics grades of 81 students aged between ten and thirteen (i.e., in Grades 5 and 6) employing the number bisection task. Results indicated that number magnitude understanding, arithmetic fact knowledge, and conceptual and procedural knowledge contributed to explaining mathematics grades even when controlling for domain-general cognitive abilities. Methodological and practical implications of the results are discussed.

1. Introduction

Being able to understand and process numbers appropriately, that is, being numerate, is essential for us to successfully manage our lives, as we are living in a world full of numbers. The crucial role numeracy plays becomes especially evident in children, adolescents, and adults who experience difficulties with numbers and arithmetic (Price & Ansari, 2013; Rubinsten & Tannock, 2010). In particular, these individuals face negative outcomes in education (i.e., poor academic achievement, math anxiety, and school phobia), occupation (i.e., major disadvantages in competing on the job market), and economic life prospects (i.e., lower income; e.g., Bynner, Parsons, & Basic Skills Agency, 1997; Parsons & Bynner, 2005; Shalev et al., 2005; Watts et al., 2014). As such, the acquisition of skills enabling individuals to understand and process numbers constitutes a crucial goal set for formal education (e.g., Baden-Württemberg Ministry of Science, Research and the Arts, 2016).

1.1. Numeracy and basic numerical abilities

Numeracy, however, does not represent a unidimensional construct (e.g., Dowker, 2008). Instead, it encompasses several basic numerical abilities for which different structural ideas have been put forth. For instance, Aunio et al. (2004, 2010) differentiated basic numerical abilities into relational (i.e., classification, seriation, nonsymbolic

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comparison) and counting abilities (i.e., structured and resultative counting, use of number words, general number understanding). Others have argued for the differentiation of symbolic (i.e., counting, naming numbers) and nonsymbolic abilities (i.e., nonsymbolic number line tasks, comparing sets of dots; e.g., Cirino, 2011; Kolkman et al., 2013), for example. Independent of which structural approach to follow, basic numerical abilities are usually assessed using a between-task approach, meaning different tasks assess the respective basic numerical abilities.

Such a between-task approach relies on the assumption that performance differences between tasks are only attributable to differences in the abilities assessed (i.e., assuming task isomorphism), but not to differences between tasks (e.g., underlying representation: verbal, semantical, or digital; output format: spoken words or button presses; interaction of the latter; overall difficulty; Moeller et al., 2009; Nuerk et al., 2002; Wood et al., 2008). However, employing a between-task approach, it is not possible to rule out that results could also be influenced by such between-task differences.

Based on the triple code model of numerical cognition (Dehaene et al., 2003; Dehaene & Cohen, 1995, 1997), another structural differentiation of basic numerical abilities can be derived. As regards the processing of numerical information, the triple code model distinguishes between i) *number magnitude understanding* (e.g., magnitude comparison; e.g., Bartelet et al., 2014; Cohen et al., 2000; Hubbard et al., 2005; Klein et al., 2016; Wood et al., 2008) and ii) verbally mediated *arithmetic fact knowledge* (e.g., multiplication tables; e.g., Delazer et al., 2003, 2004; Klein et al., 2016; Wood et al., 2008). In addition to these two basic numerical codes and one iii) coding visual Arabic symbols (Dehaene & Cohen, 1995, 1997), the model also assumes influences of iv) *conceptual* and *procedural knowledge* necessary to operate on above described numerical representations (i.e., applying appropriate rules, strategies and procedures, integrating all information to solve task at hand; e.g., Butterworth, 2005; Delazer et al., 2003; Klein et al., 2016; Semenza, 2002; Wood et al., 2008).

Different from the above described between-task approach, there is evidence that the latter basic numerical abilities can be assessed and differentiated within one and the same task (i.e., the number bisection task), and thus using a within-task approach (Delazer et al., 2006; Moeller et al., 2009, 2010; Moeller, Klein, et al., 2011; Nuerk et al., 2002; Wood et al., 2008). In its verification version, the number bisection task requires participants to indicate whether the central number of a number triplet corresponds to the arithmetic mean of the interval defined by the two outer numbers (e.g., 23_26_29) or not (e.g., 23_25_29). As described in detail by Nuerk et al. (2002), specific characteristics of number triplets can be manipulated so that associated effects primarily reflect i) *magnitude understanding* (i.e., small vs. large ranges between outer numbers: large 12–18 vs. small 4–8, e.g., 16 in 4_12_20 vs. 4 in 10_12_14; distance between the central number and the correct arithmetic mean of the interval: large 2–8 vs. small 0.5–1.5, e.g., 5 in 12_14_26 vs. 1 in 12_20_26), ii) *arithmetic fact knowledge* (i.e., triplets with numbers from a multiplication table vs. not from a multiplication table, e.g., 12_18_24 vs. 11_17_23), and iii) *conceptual* and *procedural knowledge* (i.e., bisectable vs. non-bisectable problems with parity homo- or heterogeneity, e.g., 24_27_32 has a mean of 28 vs. 24_27_31 has a mean of 27.5).

The major advantage of using a within-task approach to assess basic numerical abilities is that it allows to control for influences of task-specific differences on the effects examined (for a discussion see e.g., Nuerk et al., 2002). A within-task approach thus acknowledges that individual performance differences found between tasks may not only be attributable to different basic numerical abilities required to perform the respective tasks (e.g., magnitude understanding vs. fact retrieval), but also to differing task attributes (e.g., underlying representation, output format, interaction of the latter, overall difficulty; Moeller et al., 2009; Nuerk et al., 2002; Wood et al., 2008). Additionally, it allows to control for influences of basic numerical abilities other than the one assessed, by matching stimuli to variables reflecting other basic numeric abilities. Hence, within-task approaches substantiate that effects are attributable to specific basic numerical abilities, rather than uncontrolled differences between tasks or influences of other numerical skills.

Neurofunctional correlates of the number bisection task provide further evidence for the claim that the task may be used to assess three basic numerical abilities. First, Wood et al. (2008), but also Klein et al. (2016) demonstrated that variations of the distance between the central number of the triplet and the correct arithmetic mean of the interval were specifically associated with activation in the bilateral intraparietal sulcus (IPS) – an area typically associated with the processing of number magnitude information (Ansari et al., 2006; Arsalidou & Taylor, 2011; Cohen Kadosh et al., 2007; see Dehaene et al., 2003 for a review; Dehaene & Cohen, 1995; Price et al., 2007; Skagerlund et al., 2016). Neuropsychological evidence from patients with cerebral lesions further supports the assumption that the number bisection task can be employed to assess number magnitude processing (Cohen & Dehaene, 2000; Delazer et al., 2006; Rossetti et al., 2004; Zorzi et al., 2002). This clearly indicates that triplets differing in the distance between the central number and the correct arithmetic mean of the interval draw heavily on number magnitude processing and thus may indeed allow an assessment of this basic numerical ability.

Second, Wood et al. (2008) as well as Klein et al. (2016) further demonstrated that processing triplets, which were part of a multiplication table, was specifically associated with activation in the left angular gyrus (AG) – an area typically associated with arithmetic fact retrieval (De Visscher et al., 2015, 2018; see Dehaene et al., 2003 for a review; Grabner et al., 2009; Ischebeck et al., 2006; Lee & Kang, 2002; Rivera et al., 2005). In turn, this provides strong evidence that the multiplicativity effect as observed with the number bisection task indeed reflects processes associated with arithmetic fact retrieval. One may therefore conclude that the number bisection task, and in particular triplets differing in whether arithmetic fact knowledge concerning multiplication tables helps in solving them, are suitable to assess arithmetic fact knowledge.

Finally, Wood et al. (2008) demonstrated that the evaluation of parity in terms of the bisection possibility effect was associated with activation in brain areas that have previously been found to be involved in cognitive set shifting and the generation of alternative solutions to problems via the controlled retrieval of rule meanings (e.g., Donohue et al., 2005; Goel & Vartanian, 2004), such as the right ventrolateral prefrontal cortex (VLPFC). This seems reasonable as parity inhomogeneity of the outer numbers of the triplet allows for a rule-based alternative solution to the common strategy based on magnitude manipulation. Such rule-based strategies were considered to reflect conceptual (Moeller et al., 2009; Wood et al., 2008) and/or procedural knowledge (Mock et al., 2016; Wood et al., 2008). As such, lower error rates for bisection impossible triplets with parity inhomogeneous outer numbers may thus be due to processing parity information in a rule-based manner (check for inhomogeneity). In turn, this seems to involve aspects of both conceptual (parity) and procedural (check for inhomogeneity) knowledge. Taken together, these results provide evidence for the idea that the number bisection task may be used to assess the basic numerical abilities magnitude understanding, arithmetic fact knowledge, and conceptual and procedural knowledge in a within-task approach.

1.2. Basic numerical abilities and mathematics achievement

An increasing body of cross-sectional research in young children in kindergarten and primary school showed that basic numerical abilities such as magnitude understanding, counting skills, symbolic and non-symbolic number sense, and the understanding of mathematical relations were associated with better arithmetic skills and mathematics achievements (Aunio & Räsänen, 2016; Booth & Siegler, 2006, 2008; Cowan & Powell, 2014; Dowker, 2008; Geary et al., 2007; Holloway & Ansari, 2009; Landerl et al., 2004). Longitudinal data additionally supported the relevance of early basic numerical abilities for the development of later mathematical abilities such as fraction understanding, algebra, geometry, and calculation fluency, as well as later mathematics achievement (e.g., Aunio & Niemivirta, 2010; Bailey et al., 2014; Bartelet et al., 2014; De Smedt et al., 2009; Desoete et al., 2012; Duncan et al., 2007; Gilmore et al., 2017; Hirsch et al., 2018; Jordan et al., 2007, 2010; Libertus et al., 2013; Locuniak & Jordan, 2008; Lyons et al., 2014; Moeller, Pixner, et al., 2011; Ribner et al., 2018; Siegler et al., 2012; Watts et al., 2014).

Among the domain-specific basic numerical competencies assessed in these studies, magnitude understanding, arithmetic fact knowledge, and conceptual and procedural knowledge were consistently shown to be relevant for arithmetic achievement and the development of arithmetic skills, even after controlling for the influence of important domain-general covariates such as intelligence, working memory, but also reading performance (e.g., Bailey et al., 2014; Booth & Siegler, 2006, 2008; Cowan & Powell, 2014; Geary et al., 2007; Hirsch et al., 2018; Jordan et al., 2003, 2007; Krajewski & Schneider, 2009). Hence, basic numerical abilities should be assumed to constitute important prerequisites for the successful acquisition of mathematics as taught through formal schooling as well as for individual mathematics achievement.

Only very little is, however, known about the relevance of older students' basic numerical abilities for their mathematics achievement, hence indicating the need for further research. The few studies available nevertheless support the assumption that basic numerical abilities are still relevant for students' mathematics achievement in secondary school. Ludewig et al. (2020), for instance, showed basic numerical abilities of students in Grades 9 to 11, who were on average 17 years old, to be related to their reading performance of mathematical graphs. Additionally, Rittle-Johnson et al. (2001) demonstrated that knowledge of decimal fraction concepts (i.e., conceptual knowledge) of children in Grades 5 and 6, who were on average 12 years old, predicted gains in procedural knowledge, while their procedural knowledge also predicted gains in conceptual knowledge, respectively. These studies, however, relied on between-task approaches to assess basic numerical abilities, using separate tasks for each ability. To our knowledge, no study investigating the relevance of secondary school students' basic numerical abilities, as assessed using a within-task approach, for their mathematics achievement has been conducted before. Additionally, the few existing studies used the results of mathematics achievement tests as criterion variables. Thus, the ecological relevance of basic numerical abilities for real-life academic outcomes, that is, students' mathematics grades, is yet to be investigated.

1.3. The present study

The present study therefore aimed to evaluate the relevance of the basic numerical abilities i) number magnitude understanding, ii) arithmetic fact knowledge, and iii) conceptual and procedural knowledge for mathematics grades of students aged between ten and thirteen (i.e., in Grades 5 and 6), employing a within-task approach using the number bisection task. In line with results from studies employing a between-task approach in younger students, it was expected that all three basic numerical abilities contribute to explaining mathematics grades. Against the background of the current literature, number magnitude understanding was expected to be the most relevant basic numerical predictor, while arithmetic fact knowledge, and conceptual and procedural knowledge were expected to be less important predictors of children's mathematics grades. Additionally, domain-specific numerical abilities were expected to explain mathematics grades over the influence of domain-general cognitive abilities as reflected by students' general cognitive ability as well as their visual-spatial and verbal working memory.

2. Methods

2.1. Sample

Participants[1] were recruited from local schools and invitations sent out on the university's mailing list. The recruited sample comprised $N = 84$ children, but data from three participants had to be excluded due to missing values ($n = 2$) or misunderstood instructions regarding the number bisection task (i.e., used wrong hand to respond; $n = 1$). The final sample thus comprised $N = 81$ participants ($M_{age} = 11.27$ years, $SD_{age} = 0.68$ years; 35 female). Thirty-four participants were in Grade 5 and 47 in Grade 6. Seventy-five participants were enrolled in the academic track and two in the intermediate track. No track information was available for four participants.[2]

Recruitment in schools was approved by the Baden-Württemberg Ministry of Science, Research and the Arts. Additionally, the study was approved by the Ethics Committee for Psychological Research at the University of Tübingen. Written informed consent for study participation was obtained from both the participating children and their parents or legal guardians. Children were eligible for participation when they were in Grade 5 or 6, that is, when they were between ten and thirteen years old, and not diagnosed with epilepsy.

Participants were reimbursed for their participation with a voucher for a toy store (8 Euro). Parents were reimbursed with a voucher for a local café (4 Euro).

2.2. Procedure

Each participant attended one test session that took place in a quiet room either at a laboratory at the university or at the child's own school. The experimenter welcomed the participant and accompanying parents upon arrival and answered any open questions. Children performed the number bisection task after having attended a virtual math lesson for 15 min (see Blume et al., 2019 for further details). Finally, their general cognitive ability as well as verbal and visual-spatial working memory were assessed.[3] No test session conflicted with teaching times and only one participant was assessed at a time. Each test session took approximately 75 min, including preparation time. The data from the number bisection task analysed in the present study were collected between the 15th and the 40th minute while working memory was assessed at the end of the test session. Prior to the test session, parents filled in an online questionnaire, which lasted approximately 30 min, at home. Parents reported on their child's mathematics grade as shown in the last report, their age, as well as the school year they were in, and ADHD or dyscalculia diagnoses.[4]

2.3. Measures

2.3.1. Mathematics grades

To assess student achievement in mathematics, parent-reported mathematics grades from the children's last report card were used. School grades in Germany range from 1 (best grade) to 6 (lowest grade)

[1] The sample of the present study was already described in more detail in an earlier publication (Blume et al., 2019).

[2] The federal state in which the study was conducted, like the majority of German federal states, has a tripartite school system from Grade 5 on with lower, intermediate, and academic tracks.

[3] Children performed an additional task (i.e., the Stop Signal Task; Verbruggen et al., 2008) and answered questions concerning the instructional quality of a virtual math lesson attended and their preferred seating location in a classroom. Data from the Stop Signal Task and the questionnaires were collected to be analysed as part of other studies.

[4] Additionally, parents informed about their child's self-regulation (Rauch et al., 2014) and ADHD symptoms (Lidzba et al., 2013). These data were also collected to be analysed as part of other studies.

and are typically graded in quarter steps between the limits of 1 and 6 (e.g., 1.25). Consequently, lower grades indicated better mathematics abilities. As parents typically reported mathematics grades as decimal numbers, they were treated as a continuous variable.

2.3.2. Number bisection task

The number bisection task comprised 200 items presented on a standard laptop (screen width of 15.6 in.) and required participants to indicate whether or not the central number of a number triplet reflected the arithmetic mean of the interval spanned by the two outer numbers (e.g., 24_27_30 vs. 24_27_31, respectively; Nuerk et al., 2002). Participants indicated their answers by button presses on a German standard QWERTZ keyboard: pressing the left 'CTRL' key indicated that the central number was *not* the mean of the interval, whereas pressing the right 'CTRL' key indicated that the central number was the arithmetic mean of the triplet. Presentation time for each triplet and thus the time limit for responses was 9000 ms. When participants responded within the given time frame, the next item was presented after an inter-stimulus interval (ISI) of 1000 ms. When participants did not respond within the given time frame, their answer was coded as incorrect and the next item was presented after an ISI of 1000 ms. Each item was preceded by a fixation cross presented in the centre of the screen during the second half of the ISI. Items were presented in four blocks of 50 items each with a break of 20 s between blocks. Split-half reliability of the number bisection task was 0.95 (Spearman-Brown corrected, calculated by correlating performance on items with even and uneven numbers after sorting them by bisection possibility and problem size, i.e., the arithmetic mean of the three numbers; Blume et al., 2019).

Number triplets were composed of numbers ranging between 10 and 99 in Arabic notation. A 2 × 2 within-participant design was applied to both bisectable (e.g., 24_27_30; requiring a 'yes' answer) and non-bisectable items (e.g., 24_27_31; requiring a 'no' answer). For bisectable triplets, multiplicativity (i.e., number triplets from a multiplication table vs. triplets not from a multiplication table, e.g., 12_18_24 vs. 11_17_23) and bisection range (i.e., numerical distance between outer numbers; large 12–18 vs. small 4–8, e.g., 16 in 4_12_20 vs. 4 in 10_12_14) were varied. For non-bisectable items, bisection possibility (i.e., whether the two outer numbers had an integer mean; e.g., 24_27_32 has a mean of 28 vs. 24_27_31 has a mean of 27.5) and distance between the central number and the correct arithmetic mean of the interval (large: 2–8 vs. small: 0.5–1.5, e.g., 5 in 12_14_26 vs. 1 in 12_20_26) were manipulated. Problem size (mean of all numbers), average parity, parity homogeneity, decade crossings, and the inclusion of multiples of ten were matched across stimulus groups.

Two indices representing *number magnitude understanding* were calculated. The first was calculated as the individual difference in error rates for a) items with a large bisection range (i.e., numerical distance between outer numbers of the interval, large 12–18, e.g., 16 in 4_12_20) requiring 'yes' responses compared to b) items with a small bisection range (4–8, e.g., in 10_12_14) requiring 'yes' responses. In the remainder of this article, this difference will be referred to as the *bisection range effect*. It reflects the notion that better magnitude understanding is associated with smaller differences in error rates between items with large (i.e., more difficult) versus small (i.e., easier) intervals. The second index was calculated as the individual difference in error rates for a) items with a small distance between the correct and the presented arithmetic mean (i.e., 0.5–1.5, e.g., 1 in 12_20_26) requiring 'no' responses compared to b) items with a large distance between the correct and the presented arithmetic mean (i.e., 2–8, e.g., 5 in 12_14_26) requiring 'no' responses. This difference will be referred to as *distance to the middle effect*. It reflects the idea that better magnitude understanding is associated with smaller differences in error rates between items with a small (i.e., more difficult) versus a large distance (i.e., easier) between the presented and the correct mean.

The index representing *arithmetic fact knowledge* was calculated as the individual difference in error rates when solving a) items requiring 'yes' responses because they come from a multiplication table (e.g., 12_24_36) compared to b) items requiring 'yes' responses, but are not from a multiplication table. This was termed the *multiplicativity effect*, reflecting that better knowledge of arithmetic facts is associated with larger differences in error rates between items whose constituting numbers do not come (i.e., more difficult) versus come from a multiplication table (i.e., easier as the middle number of items from multiplication tables always represents the correct arithmetic mean of the interval).

The index representing *conceptual and procedural knowledge* was calculated as the individual difference in error rates for a) items requiring 'no' responses because they have no integer mean due to flanking numbers of differing parity (e.g., 24_27_31) compared to b) items requiring 'no' responses but have flanking numbers of the same parity (e.g., 24_27_32). This difference will be referred to as the *bisection possibility effect*. This effect reflects that increased knowledge of arithmetic strategies should lead to larger differences in error rates between items whose flanking numbers do not differ (i.e., more difficult as they require the use of additional strategies) versus differ in parity (i.e., easier as they can easily be identified as incorrect).

Data from the bisection task were first inspected for overall error rates deviating more than three standard deviations from the mean (guessing rate was 50%), which might indicate that participants had not performed the number bisection task correctly. Two participants were excluded from further analyses. Additionally, after calculation of the effects of interest (i.e., bisection range, distance to the middle, bisection possibility and multiplicativity) data were again inspected for potential outliers. Participants with effects deviating more than ±3 *SD* from the mean were excluded. This affected three participants.

2.3.3. General cognitive ability

The Matrices Span Task from the Wechsler Intelligence Scale for Children, Fourth Edition (WISC-IV; Petermann & Petermann, 2011) was used as an estimate of children's general cognitive ability. As reported in the manual, split-half reliability was $r = 0.89$ and $r = 0.91$ for the respective age groups. Scores from the Matrices Span Task are reported to correlate at $r = 0.72$ with the WISC-IV total IQ score and distinguished well between typically developing and highly gifted children (standardized difference 0.93), and between typically developing and intellectually impaired children (standardized difference 2.27). For the task, the experimenter presented children with an incomplete matrix or row of figures as well as five possible answers of which children had to select the one they thought completed the matrix or row correctly. A maximum of 35 trials with increasing difficulty could be solved, each of which was awarded 1 point when solved correctly, making a range of scores between 0 and 35 possible. When children solved four successive trials or four out of five successive trials incorrectly, the task was stopped. The number of trials solved correctly was considered as the dependent variable representing general cognitive ability in the analyses.

2.3.4. Working memory

A computerised version of the Corsi Block Tapping Task (Corsi, 1972; Mueller, 2011) was used to assess visual-spatial working memory. In this task, participants viewed nine blue blocks on the screen, of which an increasing number successively lit up for 1000 ms each. Participants had to reproduce the reversed order in which they had lit up by clicking the respective blocks using the computer's mouse. Starting with two blocks, the number of blocks lit up increased by one up to a maximum of nine blocks every time a sequence was replicated correctly in at least one of two trials. In case participants did not replicate a sequence correctly in neither of two trials, the task was stopped. The ISI was set to 1000 ms. There was no time limit for the reproduction phase. The maximum number of blocks correctly replicated, that is, the block span, was used as the index representing visual-spatial working memory. The block span could range from 0 to 9. Reliability of a non-computerised version of the task in adults was reported to be $r = 0.95$. Validity was documented by findings supporting the independence of the visual-spatial subsystems, a construct validation study, and reports on clinical findings (Schellig, 1997).

The backward version of the Digit Span Task from the Wechsler Intelligence Scale for Children (WISC-IV; Petermann & Petermann, 2011) was used to assess verbal working memory. Split-half reliability was $r = 0.71$ and $r = 0.81$ for the respective age groups. Scores from the Digit Span Task correlated at $r = 0.74$ with the WISC-IV total IQ score and distinguished between typically developing and highly gifted children (standardized difference 1.26), and between typically developing and intellectually impaired children (standardized difference 2.85). In this task, the experimenter read a successively increasing number of single-digit numerals to participants who were instructed to reproduce the numerals in reversed order. Starting with two numerals, the number of numerals increased by one up to a maximum of eight every time a sequence was correctly replicated in at least one of two trials. When participants did not replicate the sequence correctly in neither of two trials, the task was stopped. The maximum number of numerals correctly replicated reflected the digit span, representing verbal working memory, and could range from 0 to 8.

2.4. Statistical analyses

To investigate whether the three domain-specific basic numerical abilities i) number magnitude understanding, ii) arithmetic fact knowledge, and iii) conceptual and procedural knowledge would be considered in a model predicting mathematics grades, a stepwise regression analysis with bidirectional elimination and relevant predictors identified based on the Akaike information criterion corrected (AICc) was conducted. By following an information theoretical approach, the present study did not pursue the goal to test the fit of a particular a priori defined model, but rather aimed to select the model that best fitted the data from a set of several candidate models (Burnham & Anderson, 2002, 2004). Initially, the model with the minimum AICc value was considered the best fitting model. Following Burnham and Anderson (2002, 2004), however, a delta AICc < 2 (i.e., the difference between the AICc values of 'the best' and another candidate model of interest) indicated that the model with the higher AICc value seemed to fit the data equally well and should therefore be preferred. A delta AICc > 4 and < 7 indicated considerable less support for the other model of interest, and a delta AICc > 10 indicated the other model was unlikely to fit the data well. Hence, a delta AICc < 4 was chosen as a cut-off criterion, implying that models with delta AICc > 4 were considered to not fit the data well. Additionally, AICc weights (i.e., the ratios of a candidate models' delta AICc relative to the sum of delta AICcs for all candidate models; Burnham & Anderson, 2002) were calculated to evaluate the cumulative Akaike weight for each model. Cumulative Akaike weights denote the probability that the candidate model is the best among the models considered and may take values between 0 and 1. For instance, a cumulative weight of 0.95 suggests that the candidate model should be considered the best with 95% probability. To evaluate whether domain-specific abilities predicted mathematics grades while controlling for influences of domain-general abilities, general cognitive ability as well as visual-spatial and verbal working memory were considered as additional predictors.

To obtain a measure of how robust the three domain-specific basic numerical abilities (i.e., number magnitude understanding, arithmetic fact knowledge, conceptual and procedural knowledge) and domain-general covariates (i.e., general cognitive ability, verbal working memory, visual-spatial working memory) were considered in models predicting mathematics grades, the selection process described above for models best fitting the data was repeated with 1000 bootstrap samples ($n = 50$). The frequency with which the predictors were considered in the models serves as an indicator of the relevance of the different predictors for mathematics grades.

All statistical analyses were performed in the R environment (R Core Team, 2020). For the stepwise regressions, the stepAIC function from the MASS package (Venables & Ripley, 2002), adjusted for the Akaike information criterion corrected (i.e., the stepAICc function; Batáry et al., 2014), was used. To calculate further linear regression model parameters of the models identified to fit the data best, the 'lm' function of the stats package was used.

3. Results

Table 1 presents the descriptive characteristics of the sample after the exclusion of data of the two participants with error rates more than ±3 *SD* from the mean in the number bisection task.

Table 2 presents the correlations of variables reflecting basic numerical abilities, domain-general cognitive abilities, and further covariates. The bisection range effect positively correlated with the distance to the middle effect and the bisection possibility effect. Moreover, correlations between the effects of bisection range, distance to the middle, multiplicativity, and bisection possibility were small and statistically insignificant. Additionally, the bisection range effect correlated negatively with students' general cognitive ability. As smaller effects of bisection range reflect better number magnitude understanding, better

Table 1
Descriptive statistics (mean ± SD or n (%)) and ranges (observed range and [possible range]) for the analytic sample ($N = 76$).

Variable	Mean ± SD or n (%)	Observed range [Possible range]
Gender		
Male	44 (57.89)	
Female	32 (42.11)	
Age	11.29 (0.69)	10.00–12.83
Grade		
5	31 (40.79)	
6	45 (59.21)	
ADHD diagnosis	6 (7.89)	
Dyscalculia diagnosis	5 (6.58)	
Mathematics grades[a]	2.00 (0.88)	1.00–5.00 [1.00–6.00]
ER small bisection range	7.28 (7.46)	0.00–43.84 [0.00–100.00]
ER large bisection range	14.40 (11.41)	1.20–52.63 [0.00–100.00]
ER small distance to the middle	10.40 (9.19)	0.00–38.09 [0.00–100.00]
ER large distance to the middle	4.60 (5.47)	0.00–30.00 [0.00–100.00]
ER item not from multiplication table	13.22 (12.49)	0.00–70.21 [0.00–100.00]
ER item from multiplication table	12.33 (11.69)	0.00–66.67 [0.00–100.00]
ER bisection impossible	5.88 (6.68)	0.00–31.11 [0.00–100.00]
ER bisection possible	9.08 (7.94)	0.00–36.73 [0.00–100.00]
Bisection range effect	7.12 (6.79)	−5.54–24.33 [−100.00–100.00]
Distance to the middle effect	5.80 (6.24)	−4.08–23.13 [−100.00–100.00]
Multiplicativity effect	−0.20 (5.55)	−18.60–13.32 [−100.00–100.00]
Bisection possibility effect	3.21 (5.20)	−9.09–16.75 [−100.00–100.00]
General cognitive ability	23.83 (3.45)	17.00–33.00 [0.00–35.00]
Visual-spatial WM	5.75 (1.07)	3.00–8.00 [0.00–9.00]
Verbal WM	4.40 (1.14)	2.00–8.00 [0.00–8.00]

Note. [a] lower values indicate better grades; ER = error rate in percent; number magnitude understanding: bisection range effect, distance to the middle effect; arithmetic fact knowledge: multiplicativity effect; conceptual and procedural knowledge: bisection possibility effect.

Table 2
Correlations of variables of interest and covariates.

Variable	1	2	3	4	5	6	7	8	9
1. Bisection range effect	–								
2. Distance to the middle effect	0.45*	–							
3. Multiplicativity effect	−0.13	0.02	–						
4. Bisection possibility effect	0.32*	0.18	−0.01	–					
5. Age	0.19	−0.02	−0.12	−0.02	–				
6. Gender[a]	0.09	−0.08	−0.01	−0.13	0.06	–			
7. Mathematics grade[b]	0.42*	0.08	−0.13	−0.03	0.33*	0.06	–		
8. General cognitive ability	−0.40*	−0.14	0.11	−0.06	−0.03	0.04	−0.25*	–	
9. Visual-spatial WM	−0.09	0.04	0.18	−0.08	0.28*	0.13	−0.15	0.27*	–
10. Verbal WM	−0.16	−0.04	0.12	−0.09	0.17	−0.02	−0.12	0.33*	0.34*

Note. Number magnitude understanding: bisection range effect, distance to the middle effect; arithmetic fact knowledge: multiplicativity effect; conceptual and procedural knowledge: bisection possibility effect.
Pearson's correlations tested two-tailed.
* $p < .05$.
[a] male = −1, female = 1.
[b] lower values indicate better grades.

number magnitude understanding was positively associated with students' general cognitive ability. Finally, the bisection range effect, for which smaller effects reflect better number magnitude understanding, was positively associated with students' mathematics grades, for which smaller values also indicate better grades.

3.1. Considering influences of domain-specific basic numerical abilities

The stepwise regression analysis indicated that a model including the bisection range effect should initially be considered fitting the data best, as indicated by the lowest overall AICc value (Table 3, Model 1). As reflected by delta AICcs < 4, however, models additionally including the effects of bisection possibility (Table 3, Model 2), distance to the middle (Table 3, Model 3), and multiplicativity (Table 3, Model 4) fitted the data equally well. Moreover, the model considering all four domain-specific numerical predictors (Model 4) had a cumulative AICc weight of 1.00, indicating that with a probability of 100% it is the best model among those considered. Therefore, it was concluded that a model considering effects of bisection range, bisection possibility, distance to the middle, and multiplicativity (i.e., Model 4) should fit the data best. This model explained 21% of the variance in students' mathematics grades.

Inspection of the beta weights of Model 4 (see Table 4) indicated that a smaller effect of bisection range, indicating better number magnitude understanding, predicted better (i.e., smaller) mathematics grades. Also, larger effects of bisection possibility and multiplicativity, reflecting higher conceptual and procedural as well as arithmetic fact knowledge were associated with better mathematics grades. Finally, larger effects of distance to the middle, indicating poorer number magnitude understanding, predicted better mathematics grades.[5]

Table 3
Summary of the AICc, delta AICc, AICc weights, cumulative AICc weights, and R^2 of the stepwise linear regression analysis for basic numerical abilities predicting mathematics grades.

	Model	AICc	ΔAICc	AICc weight	Cumulative AICc weights	R^2
1	Bisection range effect	175.00	0.00	0.41	0.41	0.18
2	+ Bisection possibility effect	175.17	0.17	0.38	0.79	0.20
3	+ Distance to the middle effect	176.92	1.92	0.16	0.95	0.21
4	+ Multiplicativity effect	178.95	3.95	0.06	1.00	0.21

Note. Predictors of models were successively included while retaining predictors considered as part of earlier models; number magnitude understanding: bisection range effect, distance to the middle effect; arithmetic fact knowledge: multiplicativity effect; conceptual and procedural knowledge: bisection possibility effect.

Table 4
Summary of the linear regression model of basic numerical abilities predicting mathematics grades.

Variables	*B*	*SE*	*β*
Intercept	1.69	0.15	
Bisection range effect	0.065	0.017	0.49
Bisection possibility effect	−0.027	0.020	−0.16
Distance to the middle effect	−0.013	0.019	−0.084
Multiplicativity effect	−0.010	0.017	−0.064

Note. Number magnitude understanding: bisection range effect, distance to the middle effect; arithmetic fact knowledge: multiplicativity effect; conceptual and procedural knowledge: bisection possibility effect.
$R^2 = 0.21$; $F(4,66) = 4.39$, $p < .01$.

The bootstrapping approach indicated nine different models were identified that best fit the data. The model incorporating the effects of bisection range, distance to the middle, multiplicativity, and bisection possibility as predictors of mathematics grades was identified to fit the data best in 44.3% of bootstrapping cycles, the model considering the effects of bisection range, distance to the middle, and bisection possibility in 21.2%, and the model considering the effects of bisection range, multiplicativity, and bisection possibility in 21.8% of bootstrapping cycles. The six other models were identified to fit the data best in less than 2.7% of bootstrapping cycles. Most importantly, when looking at the individual predictors, the bisection range effect was considered in 99.7% and the bisection possibility effect in 90.3% and thus in virtually all of the models identified to fit the data best. The distance to the middle effect was incorporated in 74.3% and the multiplicativity effect in 75.6% of the models.

3.2. Considering influences of basic numerical and domain-general cognitive abilities

When additionally considering domain-general abilities such as general cognitive ability as well as visual-spatial and verbal working

[5] As there is a debate on whether (mathematics) grades can be considered continuous variables, we also ran an ordinal regression analysis with the effects of bisection range, distance to the middle, multiplicativity, and bisection possibility predicting students' mathematics grades using the 'polr' function of the MASS package (Venables & Ripley, 2002). Inspection and comparison of regression weights and confidence intervals of the linear and the ordinal regression model indicated comparable results. Hence, students' mathematics grades were treated as continuous variables for the current analyses.

memory, the stepwise regression analysis indicated that the model only incorporating the effect of bisection range had the lowest AICc and hence initially presented as the best model (Table 5, Model 1). Nevertheless, as indicated by delta AICcs < 4, a model considering the effects of bisection possibility and distance to the middle as well as visual-spatial working memory as additional predictors fitted the data equally well (Table 5, Model 4). Finally, as the cumulative weight of all models with a delta AICc < 4 was 0.96, indicating that with a probability of 96% model 4 is the best among those considered, it was concluded that this model should fit the data best: explaining about 21% of the variance in students' mathematics grades.

Inspection of the beta weights of Model 4 (see Table 6) indicated that smaller effects of bisection range, reflecting better number magnitude understanding, predicted better (i.e., smaller) mathematics grades. Additionally, larger effects of bisection possibility and distance to the middle, reflecting better conceptual and procedural and poorer magnitude understanding, were associated with better mathematics grades. Finally, larger effects of distance to the middle, indicating poorer number magnitude understanding, predicted better mathematics grades.[5]

The bootstrapping approach identified a total of 59 different models to fit the data best. Of these, 53 incorporated a combination of domain-specific and domain-general predictors, while five incorporated only domain-specific predictors (i.e., basic numerical abilities). Models considering domain-general and domain-specific predictors were identified to fit the data best in 96.0% of bootstrapping cycles. The model considering the effects of bisection range, distance to the middle, multiplicativity, bisection possibility, as well as general cognitive ability, visual-spatial, and verbal working memory (i.e., all predictors) was identified to fit the data best in 49.2% of bootstrapping cycles. All other models were identified to best fit the data only rarely ($M = 0.97\%$, $SD = 0.79$, $Min = 0.1\%$, $Max = 3.1\%$). Importantly, as regards the frequency with which basic numerical predictors were considered in the best-fitting models, the bisection range effect was incorporated in the vast majority of 98.6% of the models and the bisection possibility effect was considered in 88.5% of the models. The distance to the middle effect was considered in 78.9% of the models, and the multiplicativity effect in 82.3%. Beyond basic numerical abilities, general cognitive ability was considered in 72.8% of the models identified to fit the data best, while verbal working memory was considered in 75.1%, and visual-spatial working memory in 73.9% of the models.

Table 5
Summary of the AICc, delta AICc, AICc weights, cumulative AICc weights, and R^2 of the stepwise linear regression analysis for basic numerical abilities and domain-general abilities predicting mathematics grades.

	Model	AICc	ΔAICc	AICc weight	Cumulative AICc weights	R^2
1	Bisection range effect	173.42	0.00	0.38	0.41	0.18
2	+ Bisection possibility effect	173.67	0.25	0.33	0.71	0.20
3	+ Visual-spatial WM	174.88	1.46	0.18	0.89	0.21
4	+ Distance to the middle effect	176.71	3.29	0.07	0.96	0.21
5	+ Multiplicativity effect	178.84	5.42	0.03	0.99	0.22
6	+ General cognitive ability	181.14	7.72	<0.01	0.99	0.22
7	+ Verbal WM	183.73	10.31	<0.01	1.00	0.21

Note. Predictors of models were successively included while retaining predictors considered as part of earlier models; number magnitude understanding: bisection range effect, distance to the middle effect; arithmetic fact knowledge: multiplicativity effect; conceptual and procedural knowledge: bisection possibility effect.

Table 6
Summary of the linear regression model of basic numerical and domain-general abilities predicting mathematics grades.

Variables	*B*	*SE*	*β*
Intercept	2.24	0.55	
Bisection range effect	0.065	0.016	0.49
Bisection possibility effect	−0.027	0.020	−0.16
Visual-spatial WM	−0.095	0.090	−0.12
Distance to the middle effect	−0.013	0.018	−0.088

Note. Number magnitude understanding: bisection range effect, distance to the middle effect; conceptual and procedural knowledge: bisection possibility effect. $R^2 = 0.22$; $F(4,66) = 4.64$, $p < .01$.

4. Discussion

The present study employed a within-task approach (Nuerk et al., 2002) to assess the performance of students aged between ten and thirteen (i.e., in Grades 5 and 6) on three domain-specific basic numerical abilities, these are i) *number magnitude understanding*, ii) *arithmetic fact knowledge*, and iii) *conceptual and procedural knowledge*. At the core of its research objectives, the study aimed to identify the best fitting model predicting students' mathematics grades based on these basic numerical abilities in a first step and a combination of basic numerical as well as domain-general cognitive abilities considering influences of general cognitive ability, verbal, and visual-spatial working memory in a second step.

The results supported our expectation that all three basic numerical abilities should be important predictors of secondary school students' mathematics grades. In fact, it was observed that a model considering number magnitude understanding, arithmetic fact knowledge, and conceptual and procedural knowledge (as reflected by effects of bisection range and distance to the middle, multiplicativity, and bisection possibility, respectively) to predict students' mathematics grades fitted the data best. Furthermore, the results of the bootstrapping approach identifying 1000 best fitting models based on randomly chosen subsamples of 50 students substantiated that number magnitude understanding as reflected by the bisection range effect and conceptual and procedural knowledge as reflected by the bisection possibility effect were considered in almost all models (> 90%) identified to fit the data best. Additionally, arithmetic fact knowledge as reflected by the multiplicativity effect was considered in more than 75% and number magnitude understanding as reflected by the distance to the middle effect in more than 74% of the best fitting models.

As such, our results are in line with prior research employing between-task approaches, showing that a variety of different basic numerical abilities – including number magnitude understanding, arithmetic fact as well as conceptual and procedural knowledge – were associated with and predicted current and later mathematics achievement in younger children (e.g., Aunio & Niemivirta, 2010; Bailey et al., 2014; Cowan & Powell, 2014; Desoete et al., 2012; Hirsch et al., 2018; Lyons et al., 2014; Siegler et al., 2012). Moreover, the current results fit earlier evidence indicating that number magnitude understanding seemed to be a particularly relevant predictor of children's arithmetic achievement (e.g., Bailey et al., 2014; Lyons et al., 2014). The results showing that conceptual and procedural knowledge as reflected by the bisection possibility effect were additionally considered in almost all models further complement existing research.

Finally, our results also corroborated the expectation that domain-specific basic numerical abilities are relevant predictors of students' mathematics grades even when domain-general cognitive abilities were considered in the respective models. This is reflected by the result that number magnitude understanding and conceptual and procedural knowledge remained relevant predictors of mathematics grades even when visual-spatial working memory was considered in the final model derived on the basis of its AICc values. The results of the bootstrapping approach again substantiated this initial result. Number magnitude understanding as reflected by the effects of bisection range and distance to the middle, conceptual and procedural knowledge as indicated by the bisection possibility effect, and arithmetic fact knowledge as indicated by the multiplicativity effect were considered in the vast majority (i.e., > 80%) of best fitting models also considering domain-general predictors. Again, this is in line with prior research (Bailey et al., 2014; Booth & Siegler, 2006, 2008; Cowan & Powell, 2014; Geary et al., 2007; Jordan et al., 2007).

Apart from these findings, which are at the core of our research question, the finding that a larger effect of distance to the middle, indicating poorer magnitude understanding, was associated with better mathematics grades in both models identified to best fit the data based on their AICc values deserves further discussion. In general, empirical findings on the predictive value of the distance effect are mixed. For instance, Holloway and Ansari (2009) demonstrated a smaller distance effect to be associated with better mathematical abilities in typically developing children (see also e.g., De Smedt et al., 2009). In contrast, Moeller, Pixner, et al. (2011) found a larger distance effect to be associated with better performance in a comparable sample (Rousselle & Noël, 2007). In an attempt to explain these inconsistent findings, Moeller, Pixner, et al. (2011) argued that associations of the distance effect with mathematical achievement may not be monotone but influenced by the difficulty of the task based on which the distance effect is estimated. It is difficult to evaluate the difficulty of the number bisection task compared to number magnitude comparison tasks usually used to estimate numerical distance effects. Nevertheless, strategies other than magnitude comparison may well have been employed in the current number bisection task, which may be one reason for the observed negative association with mathematics grades (see Moeller, Pixner, et al., 2011 for a more detailed discussion).

4.1. Methodological and practical implications

In line with previous research using a between-task approach (i.e., basic numerical abilities were assessed using different tasks; e.g., Aunio & Niemivirta, 2010; Bailey et al., 2014; Cowan & Powell, 2014; Desoete et al., 2012; Hirsch et al., 2018; Lyons et al., 2014; Siegler et al., 2012), the present results of a within-task approach substantiated that several basic numerical abilities could be assessed using one and the same task and were relevant predictors of children's mathematics achievement measured through their mathematics grades. Thereby, the present study demonstrated that the proposed within-task approach may be an ecologically valid and theoretically warranted alternative to be used in children to assess their basic numerical abilities. This argument is further substantiated by the finding that a model including domain-specific numerical abilities as well as domain-general cognitive abilities was selected to best predict mathematics achievement (Bailey et al., 2014; Booth & Siegler, 2006, 2008; Cowan & Powell, 2014; Geary et al., 2007; Hirsch et al., 2018; Jordan et al., 2007). As differences in basic numerical abilities could be attributed to task differences in the current study (cf. Moeller et al., 2009; Nuerk et al., 2002; Wood et al., 2008), which was furthermore supported by weak associations between the effects assumed to reflect different numeric abilities, within-task approaches seem to be a preferable alternative to between-task approaches to be used in future research.

Beyond this methodological implication, results of the present study also have a practical implication: the finding that basic numerical abilities (i.e., number magnitude understanding, arithmetic fact knowledge, conceptual and procedural knowledge) should be considered relevant predictors of mathematics grades of students aged between ten and thirteen (i.e., in Grades 5 and 6) substantiates the idea that basic numerical competences should also be considered in secondary school mathematics education. Although primarily proclaimed as a learning goal for primary school (i.e., until the end of Grade 4; Ministry of Education and Cultural Affairs Baden-Württemberg, 2016), not all children may have mastered to, for instance, manipulate magnitudes, and thus still experience difficulties with arithmetic. As suggested by our data, this may result in poorer mathematics grades in secondary school, where mathematics education moves on beyond calculating. As such, continuous screening and further training might be reasonable also in secondary school. Earlier studies already provided support for the assumption that basic numerical and arithmetic abilities can be improved by training in kindergarten and primary school (e.g., Räsänen et al., 2009; van der Ven et al., 2017). This might, for instance, also be accomplished by using arithmetic games (Kiili et al., 2018; Ninaus et al., 2017; van der Ven et al., 2017). Whether training basic numerical abilities of children aged between ten and thirteen (i.e., in Grades 5 and 6) would also improve mathematics grades should, however, be investigated in further research.

4.2. Limitations & perspectives

To the best of our knowledge, the present study was the first to employ a within-task approach to investigate the relevance of basic numerical abilities for mathematics grades of students aged between ten and thirteen (i.e., in Grades 5 and 6). Future studies aiming to replicate and extend these findings may consider the following limitations. First, the present study followed an information theoretic approach with the aim to identify the model fitting the data best from a set of candidate models. Therefore, further studies are needed to evaluate whether the selected models are substantiated by new data (i.e., following frequentist statistical approaches).

Additionally, in examining the relevance of the basic numerical abilities i) number magnitude understanding, ii) arithmetic fact knowledge, and iii) conceptual and procedural knowledge for students' mathematics grades, the present study only acknowledged three operationalisations of basic numerical abilities whereas others exist and have been evaluated using between-task approaches (e.g., relational and counting skills, symbolic and nonsymbolic abilities; Hirsch et al., 2018). Hence, generalisation of the present results to basic numerical abilities beyond those assessed is not possible so far. Future research may therefore wish to extend the within-task approach to further conceptualizations of basic numerical abilities when evaluating their relevance for students' mathematics grades in secondary school.

Moreover, empirical support for the assumption that the bisection possibility effect reflects conceptual and procedural knowledge is relatively weak. Wood et al. (2008) showed that the evaluation of parity in terms of the bisection possibility effect was associated with activation in brain areas that have previously been found to be involved in cognitive set shifting and the generation of alternative solutions to problems via the controlled retrieval of rule meanings (e.g., Donohue et al., 2005; Goel & Vartanian, 2004), such as the right ventrolateral prefrontal cortex (VLPFC). Such rule-based strategies were considered to reflect conceptual (Moeller et al., 2009; Wood et al., 2008) and/or procedural knowledge (Mock et al., 2016; Wood et al., 2008). However, this state of affairs clearly requires future studies validating the claim that the bisection possibility effect indeed reflects conceptual and/or procedural knowledge.

Furthermore, using students' mathematics grades as the criterion variable, the present investigation only obtained information on mathematics achievements during one term of the school year. These grades might thus reflect students' achievements related to precise learning contents covered in the respective term only (e.g., concepts of decimals, fractions, measuring and units, geometry, probability theory according to the respective curriculum; Ministry of Education and Cultural Affairs Baden-Württemberg, 2016). Hence, it is possible that, for instance, number magnitude understanding was found to be associated with students' mathematics grades most prominently because it was specifically related to certain teaching content (e.g., understanding the magnitude related concept of fractions). Future research should therefore consider more specific information on grade-related learning content. This would allow evaluating whether the relation between basic numerical abilities and students' mathematics grades holds generally or is specific to particular learning contents.

Finally, the present investigation's sample almost entirely comprised students from academic track schools (i.e., highest track of German tripartite secondary school system). Thus, it is not possible to generalise results to students of other school tracks. Future studies should therefore be concerned with examining whether the relevance of domain-specific numerical predictors for mathematics achievement also holds for students attending lower or intermediate track schools.

5. Conclusion

The present study employed a within-task approach to evaluate the relevance of basic numerical abilities for children's mathematics achievement (i.e., mathematics grades) in early secondary school. It was observed that number magnitude understanding, arithmetic fact knowledge, and conceptual and procedural knowledge were relevant predictors of students' mathematics achievement, even when controlling for influences of domain-general cognitive abilities. These results demonstrate that basic numerical abilities keep their importance for children's mathematics abilities beyond the very early school years.

CRediT authorship contribution statement

Friederike Blume: Conceptualisation, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Project Administration, Funding Acquisition, Supervision.
Thomas Dresler: Conceptualisation, Formal Analysis, Writing - Review & Editing, Supervision.
Caterina Gawrilow: Writing - Review & Editing.
Ann-Christine Ehlis: Writing - Review & Editing.
Richard Goellner: Writing - Review & Editing.
Korbinian Moeller: Conceptualisation, Methodology, Formal Analysis, Resources, Writing - Review & Editing, Supervision.

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Declaration of competing interest

The authors declare that there is no conflict of interest.

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References

Ansari, D., Fugelsang, J. A., Dhital, B., & Venkatraman, V. (2006). Dissociating response conflict from numerical magnitude processing in the brain: An event-related fMRI study. *NeuroImage, 32*(2), 799–805. https://doi.org/10.1016/j.neuroimage.2006.04.184

Arsalidou, M., & Taylor, M. J. (2011). Is 2 + 2 = 4? Meta-analyses of brain areas needed for numbers and calculations. *NeuroImage, 54*(3), 2382–2393. https://doi.org/10.1016/j.neuroimage.2010.10.009

Aunio, P., Ee, J., Lim, S. E. A., Hautamäki, J., & Van Luit, J. (2004). Young children's number sense in Finland, Hong Kong and Singapore. *International Journal of Early Years Education, 12*(3), 195–216. https://doi.org/10.1080/0966976042000268681

Aunio, P., & Niemivirta, M. (2010). Predicting children's mathematical performance in grade one by early numeracy. *Learning and Individual Differences, 20*(5), 427–435. https://doi.org/10.1016/j.lindif.2010.06.003

Aunio, P., & Räsänen, P. (2016). Core numerical skills for learning mathematics in children aged five to eight years – A working model for educators. *European Early Childhood Education Research Journal, 24*(5), 684–704. https://doi.org/10.1080/1350293X.2014.996424

Bailey, D. H., Siegler, R. S., & Geary, D. C. (2014). Early predictors of middle school fraction knowledge. *Developmental Science, 17*(5), 775–785. https://doi.org/10.1111/desc.12155

Bartelet, D., Vaessen, A., Blomert, L., & Ansari, D. (2014). What basic number processing measures in kindergarten explain unique variability in first-grade arithmetic proficiency? *Journal of Experimental Child Psychology, 117*(1), 12–28. https://doi.org/10.1016/j.jecp.2013.08.010

Batáry, P., Fronczek, S., Normann, C., Scherber, C., & Tscharntke, T. (2014). How do edge effect and tree species diversity change bird diversity and avian nest survival in Germany's largest deciduous forest? *Forest Ecology and Management, 319*, 44–50. https://doi.org/10.1016/j.foreco.2014.02.004

Blume, F., Göllner, R., Moeller, K., Dresler, T., Ehlis, A.-C., & Gawrilow, C. (2019). Do students learn better when seated close to the teacher? A virtual classroom study considering individual levels of inattention and hyperactivity-impulsivity. *Learning and Instruction, 61*, 138–147. https://doi.org/10.1016/j.learninstruc.2018.10.004

Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology, 42*(1), 189–201. https://doi.org/10.1037/0012-1649.41.6.189

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development, 79*(4), 1016–1031. https://doi.org/10.1111/j.1467-8624.2008.01173.x

Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference* (2nd ed.). Springer.

Burnham, K. P., & Anderson, D. R. (2004). Multimodel Inference. *Sociological Methods & Research, 33*(2), 261–304. https://doi.org/10.1177/0049124104268644

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry, 46*(1), 3–18. https://doi.org/10.1111/j.1469-7610.2004.00374.x

Bynner, J. M., Parsons, S., & Basic Skills Agency. (1997). *Does numeracy matter? Evidence from the National Child Development.* Basic Skills Agency: Study on the impact of poor numeracy on adult life. https://eric.ed.gov/?id=ED406585.

Cirino, P. T. (2011). The interrelationships of mathematical precursors in kindergarten. *Journal of Experimental Child Psychology, 108*(4), 713–733. https://doi.org/10.1016/j.jecp.2010.11.004

Cohen Kadosh, R., Cohen Kadosh, K., Schuhmann, T., Kaas, A., Goebel, R., Henik, A., & Sack, A. T. (2007). Virtual dyscalculia induced by parietal-lobe TMS impairs automatic magnitude processing. *Current Biology, 17*(8), 689–693. https://doi.org/10.1016/j.cub.2007.02.056

Cohen, L., & Dehaene, S. (2000). Calculating without reading: Unsuspected residual abilities in pure alexia. *Cognitive Neuropsychology, 17*(6), 563–583. https://doi.org/10.1080/02643290050110656

Cohen, L., Dehaene, S., Chochon, F., Lehéricy, S., & Naccache, L. (2000). Language and calculation within the parietal lobe: A combined cognitive, anatomical and fMRI study. *Neuropsychologia, 38*(10), 1426–1440. https://doi.org/10.1016/S0028-3932(00)00038-5

Corsi, P. M. (1972). Human memory and the medial temporal region of the brain. Dissertation Abstracts International, 34(2-B), 891.

Cowan, R., & Powell, D. (2014). The contributions of domain-general and numerical factors to third-grade arithmetic skills and mathematical learning disability. *Journal of Educational Psychology, 106*(1), 214–229. https://doi.org/10.1037/a0034097

De Smedt, B., Verschaffel, L., & Ghesquière, P. (2009). The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *Journal of Experimental Child Psychology, 103*(4), 469–479. https://doi.org/10.1016/j.jecp.2009.01.010

De Visscher, A., Berens, S. C., Keidel, J. L., Noël, M. P., & Bird, C. M. (2015). The interference effect in arithmetic fact solving: An fMRI study. *NeuroImage, 116*, 92–101. https://doi.org/10.1016/j.neuroimage.2015.04.063

De Visscher, A., Vogel, S. E., Reishofer, G., Hassler, E., Koschutnig, K., De Smedt, B., & Grabner, R. H. (2018). Interference and problem size effect in multiplication fact solving: Individual differences in brain activations and arithmetic performance. *NeuroImage, 172*, 718–727. https://doi.org/10.1016/j.neuroimage.2018.01.060

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition, 1*, 83–120.

Dehaene, S., & Cohen, L. (1997). Cerebral pathways for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic. *Cortex, 33*(2), 219–250. https://doi.org/10.1016/S0010-9452(08)70002-9

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*(3–6), 487–506. https://doi.org/10.1080/02643290244000239

Delazer, M., Domahs, F., Bartha, L., Brenneis, C., Lochy, A., Trieb, T., & Benke, T. (2003). Learning complex arithmetic—An fMRI study. *Cognitive Brain Research, 18*(1), 76–88. https://doi.org/10.1016/j.cogbrainres.2003.09.005

Delazer, M., Domahs, F., Lochy, A., Karner, E., Benke, T., & Poewe, W. (2004). Number processing and basal ganglia dysfunction: A single case study. *Neuropsychologia, 42*(8), 1050–1062. https://doi.org/10.1016/j.neuropsychologia.2003.12.009

Delazer, M., Karner, E., Zamarian, L., Donnemiller, E., & Benke, T. (2006). Number processing in posterior cortical atrophy—A neuropsycholgical case study. *Neuropsychologia, 44*(1), 36–51. https://doi.org/10.1016/j.neuropsychologia.2005.04.013

Desoete, A., Ceulemans, A., De Weerdt, F., & Pieters, S. (2012). Can we predict mathematical learning disabilities from symbolic and non-symbolic comparison tasks in kindergarten? Findings from a longitudinal study. *British Journal of Educational Psychology, 82*(1), 64–81. https://doi.org/10.1348/2044-8279.002002

Donohue, S. E., Wendelken, C., Crone, E. A., & Bunge, S. A. (2005). Retrieving rules for behaviour from long-term memory. *NeuroImage, 26*, 1140–1149.

Dowker, A. (2008). Individual differences in numerical abilities in preschoolers. *Developmental Science, 11*(5), 650–654. https://doi.org/10.1111/j.1467-7687.2008.00713.x

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., … Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428

Geary, D. C., Hoard, M. K., Byrd-Craven, J., Nugent, L., & Numtee, C. (2007). Cognitive mechanisms underlying achievement deficits in children with mathematical learning disability. *Child Development, 78*(4), 1343–1359. https://doi.org/10.1111/j.1467-8624.2007.01069.x

Gilmore, C., Keeblea, S., Richardson, S., & Cragg, L. (2017). The interaction of procedural skill, conceptual understanding and working memory in early mathematics achievement. *Journal of Numerical Cognition, 3*(2), 400–416. https://doi.org/10.5964/jnc.v3i2.51

Goel, V., & Vartanian, O. (2004). Dissociating the roles of right ventral lateral and dorsal lateral prefrontal cortex in generation and maintenance of hypotheses in set-shift problems. *Cerebral Cortex, 15*(8), 1170–1177. https://doi.org/10.1093/cercor/bhh217

Grabner, R. H., Ansari, D., Koschutnig, K., Reishofer, G., Ebner, F., & Neuper, C. (2009). To retrieve or to calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem solving. *Neuropsychologia, 47*(2), 604–608. https://doi.org/10.1016/j.neuropsychologia.2008.10.013

Hirsch, S., Lambert, K., Coppens, K., & Moeller, K. (2018). Basic numerical competences in large-scale assessment data: Structure and long-term relevance. *Journal of Experimental Child Psychology, 167*, 32–48. https://doi.org/10.1016/j.jecp.2017.09.015

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology, 103*(1), 17–29. https://doi.org/10.1016/j.jecp.2008.04.001

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience, 6*(6), 435–448. https://doi.org/10.1038/nrn1684

Ischebeck, A., Zamarian, L., Siedentopf, C., Koppelstätter, F., Benke, T., Felber, S., & Delazer, M. (2006). How specifically do we learn? Imaging the learning of multiplication and subtraction. *NeuroImage, 30*(4), 1365–1375. https://doi.org/10.1016/j.neuroimage.2005.11.016

Jordan, N. C., Glutting, J., & Ramineni, C. (2010). The importance of number sense to mathematics achievement in first and third grades. *Learning and Individual Differences, 20*(2), 82–88. https://doi.org/10.1016/j.lindif.2009.07.004

Jordan, N. C., Hanich, L. B., & Kaplan, D. (2003). Arithmetic fact mastery in young children: A longitudinal investigation. *Journal of Experimental Child Psychology, 85*(2), 103–119. https://doi.org/10.1016/S0022-0965(03)00032-8

Jordan, N. C., Kaplan, D., Locuniak, M. N., & Ramineni, C. (2007). Predicting first-grade math achievement from developmental number sense trajectories. *Learning Disabilities Research & Practice, 22*(1), 36–46. https://doi.org/10.1111/j.1540-5826.2007.00229.x

Kiili, K., Moeller, K., & Ninaus, M. (2018). Evaluating the effectiveness of a game-based rational number training - in-game metrics as learning indicators. *Computers & Education, 120*, 13–28. https://doi.org/10.1016/j.compedu.2018.01.012

Klein, E., Suchan, J., Moeller, K., Karnath, H.-O., Knops, A., Wood, G., … Willmes, K. (2016). Considering structural connectivity in the triple code model of numerical cognition: Differential connectivity for magnitude processing and arithmetic facts. *Brain Structure and Function, 221*(2), 979–995. https://doi.org/10.1007/s00429-014-0951-1

Kolkman, M. E., Kroesbergen, E. H., & Leseman, P. P. M. (2013). Early numerical development and the role of non-symbolic and symbolic skills. *Learning and Instruction, 25*, 95–103. https://doi.org/10.1016/j.learninstruc.2012.12.001

Krajewski, K., & Schneider, W. (2009). 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, 19*, 513–526. https://doi.org/10.1016/j.learninstruc.2008.10.002

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. *Cognition, 93*(2), 99–125. https://doi.org/10.1016/j.cognition.2003.11.004

Lee, K. M., & Kang, S. Y. (2002). Arithmetic operation and working memory: Differential suppression in dual tasks. *Cognition, 83*(3), 63–68. https://doi.org/10.1016/S0010-0277(02)00010-0

Libertus, M. E., Feigenson, L., & Halberda, J. (2013). Is approximate number precision a stable predictor of math ability? *Learning and Individual Differences, 25*, 126–133. https://doi.org/10.1016/j.lindif.2013.02.001

Lidzba, K., Christiansen, H., & Drechsler, R. (2013). Conners Skalen zu Aufmerksamkeit und Verhalten-3. Deutschsprachige Adaption der Conners 3rd Edition von Keith Conners. [German translation of the Conners 3rd Edition]. Huber.

Locuniak, M. N., & Jordan, N. C. (2008). Using kindergarten number sense to predict calculation fluency in second grade. *Journal of Learning Disabilities, 41*(5), 451–459. https://doi.org/10.1177/0022219408321126

Ludewig, U., Lambert, K., Dackermann, T., Scheiter, K., & Möller, K. (2020). Influences of basic numerical abilities on graph reading performance. *Psychological Research, 84*, 1198–1210. https://doi.org/10.1007/s00426-019-01144-y

Lyons, I. M., Price, G. R., Vaessen, A., Blomert, L., & Ansari, D. (2014). Numerical predictors of arithmetic success in grades 1-6. *Developmental Science, 17*(5), 714–726. https://doi.org/10.1111/desc.12152

Baden-Württemberg Ministry of Science, Research and the Arts (2016). *Education Plan*. www.bildungsplaene-bw.de.

Mock, J., Huber, S., Klein, E., & Moeller, K. (2016). Insights into numerical cognition: Considering eye-fixations in number processing and arithmetic. *Psychological Research, 80*, 334–359. https://doi.org/10.1007/s00426-015-0739-9

Moeller, K., Fischer, M. H., Nuerk, H.-C., & Willmes, K. (2009). Eye fixation behaviour in the number bisection task: Evidence for temporal specificity. *Acta Psychologica, 131*(3), 209–220. https://doi.org/10.1016/j.actpsy.2009.05.005

Moeller, K., Klein, E., Fischer, M. H., Nuerk, H.-C., & Willmes, K. (2011). Representation of multiplication facts-evidence for partial verbal coding. *Behavioral and Brain Functions, 7*(1), 25. https://doi.org/10.1186/1744-9081-7-25

Moeller, K., Pixner, S., Zuber, J., Kaufmann, L., & Nuerk, H.-C. (2011). Early place-value understanding as a precursor for later arithmetic performance—A longitudinal study on numerical development. *Research in Developmental Disabilities, 32*(5), 1837–1851. https://doi.org/10.1016/j.ridd.2011.03.012

Moeller, K., Wood, G., Doppelmayr, M., & Nuerk, H.-C. (2010). Oscillatory EEG correlates of an implicit activation of multiplication facts in the number bisection task. *Brain Research, 1320*, 85–94. https://doi.org/10.1016/j.brainres.2010.01.005

Mueller, S. T. (2011). The PEBL Corsi Block Test.

Ninaus, M., Kiili, K., McMullen, J., & Moeller, K. (2017). Assessing fraction knowledge by a digital game. *Computers in Human Behavior, 70*, 197–206. https://doi.org/10.1016/j.chb.2017.01.004

Nuerk, H.-C., Geppert, B. E., van Herten, M., & Willmes, K. (2002). On the impact of different number representations in the number bisection task. *Cortex, 38*(5), 691–715. https://doi.org/10.1016/S0010-9452(08)70038-8

Parsons, S., & Bynner, J. M. (2005). *Does numeracy matter more?* (The National Research and Development Centre for Adult Literacy and Numeracy).

Petermann, F., & Petermann, U. (2011). *Wechsler intelligence scale for children* (4th ed.). Pearson Assessment: Deutsche Bearbeitung.

Price, G. R., & Ansari, D. (2013). Dyscalculia: Characteristics, causes, and treatments. *Numeracy, 6*(1). https://doi.org/10.5038/1936-4660.6.1.2

Price, G. R., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology, 17*(24), R1042–R1043. https://doi.org/10.1016/j.cub.2007.10.013

R Core Team. (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing https://www.r-project.org/.

Räsänen, P., Salminen, J., Wilson, A. J., Aunio, P., & Dehaene, S. (2009). Computer-assisted intervention for children with low numeracy skills. *Cognitive Development, 24*(4), 450–472. https://doi.org/10.1016/j.cogdev.2009.09.003

Rauch, W. A., Gawrilow, C., Schermelleh-Engel, K., & Schmitt, K. (2014). Dispositionelle Selbstkontrollkapazität bei Kindern. *Diagnostica, 60*(2), 61–72. https://doi.org/10.1026/0012-1924/a000099

Ribner, A., Moeller, K., Willoughby, M., & Blair, C. (2018). Cognitive abilities and mathematical competencies at school entry. *Mind, Brain, and Education, 12*(4), 175–185. https://doi.org/10.1111/mbe.12160

Rittle-Johnson, B., Siegler, R. S., & Alibali, M. W. (2001). Developing conceptual understanding and procedural skill in mathematics: An iterative process. *Journal of Educational Psychology, 93*(2), 346–362. https://doi.org/10.1037/0022-0663.93.2.346

Rivera, S. M., Reiss, A. L., Eckert, M. A., & Menon, V. (2005). Developmental changes in mental arithmetic: Evidence for increased functional specialization in the left inferior parietal cortex. *Cerebral Cortex, 15*(11), 1779–1790. https://doi.org/10.1093/cercor/bhi055

Rossetti, Y., Jacquin-Courtois, S., Rode, G., Ota, H., Michel, G., & Boisson, D. (2004). Does action make the link between number and space representation? Visuo-manual adaptation improves number bisection in unilateral neglect. *Psychological Science, 15*(6), 426–430. https://doi.org/10.1111/j.0956-7976.2004.00696.x

Rousselle, L., & Noël, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition, 102*(3), 361–395. https://doi.org/10.1016/j.cognition.2006.01.005

Rubinsten, O., & Tannock, R. (2010). Mathematics anxiety in children with developmental dyscalculia. *Behavioral and Brain Functions, 6*(1), 46. https://doi.org/10.1186/1744-9081-6-46

Schellig, D. (1997). *Block-tapping-test (BTT)* (Pearson Assessment).

Semenza, C. (2002). Conceptual knowledge in arithmetic: The core of calculation skills. *Cortex, 38*(3), 285–288. https://doi.org/10.1016/S0010-9452(08)70660-9

Shalev, R. S., Manor, O., & Gross-Tsur, V. (2005). Developmental dyscalculia: A prospective six-year follow-up. *Developmental Medicine & Child Neurology, 47*(2), 121–125. https://doi.org/10.1017/S0012162205000216

Siegler, R. S., Duncan, G. J., Davis-Kean, P. E., Duckworth, K., Claessens, A., Engel, M., … Chen, M. (2012). Early predictors of high school mathematics achievement. *Psychological Science, 23*(7), 691–697. https://doi.org/10.1177/0956797612440101

Skagerlund, K., Karlsson, T., & Träff, U. (2016). Magnitude processing in the brain: An fMRI study of time, space, and numerosity as a shared cortical system. *Frontiers in Human Neuroscience, 10*(500). https://doi.org/10.3389/fnhum.2016.00500

van der Ven, F., Segers, E., Takashima, A., & Verhoeven, L. (2017). Effects of a tablet game intervention on simple addition and subtraction fluency in first graders. *Computers in Human Behavior, 72*, 200–207. https://doi.org/10.1016/j.chb.2017.02.031

Venables, W. N., & Ripley, B. D. (2002). *Modern applied statistics with S* (4th ed.). Springer.

Verbruggen, F., Logan, G. D., & Stevens, M. A. (2008). STOP-IT: Windows executable software for the stop-signal paradigm. *Behavior Research Methods, 40*, 479–483.

Watts, T. W., Duncan, G. J., Siegler, R. S., & Davis-Kean, P. E. (2014). What's past is prologue. *Educational Researcher, 43*(7), 352–360. https://doi.org/10.3102/0013189X14553660

Wood, G., Nuerk, H.-C., Moeller, K., Geppert, B., Schnitker, R., Weber, J., & Willmes, K. (2008). All for one but not one for all: How multiple number representations are recruited in one numerical task. *Brain Research, 1187*, 154–166. https://doi.org/10.1016/j.brainres.2007.09.094

Zorzi, M., Priftis, K., & Umiltà, C. (2002). Brain damage: Neglect disrupts the mental number line. *Nature, 417*, 138–139. https://doi.org/10.1038/417138a