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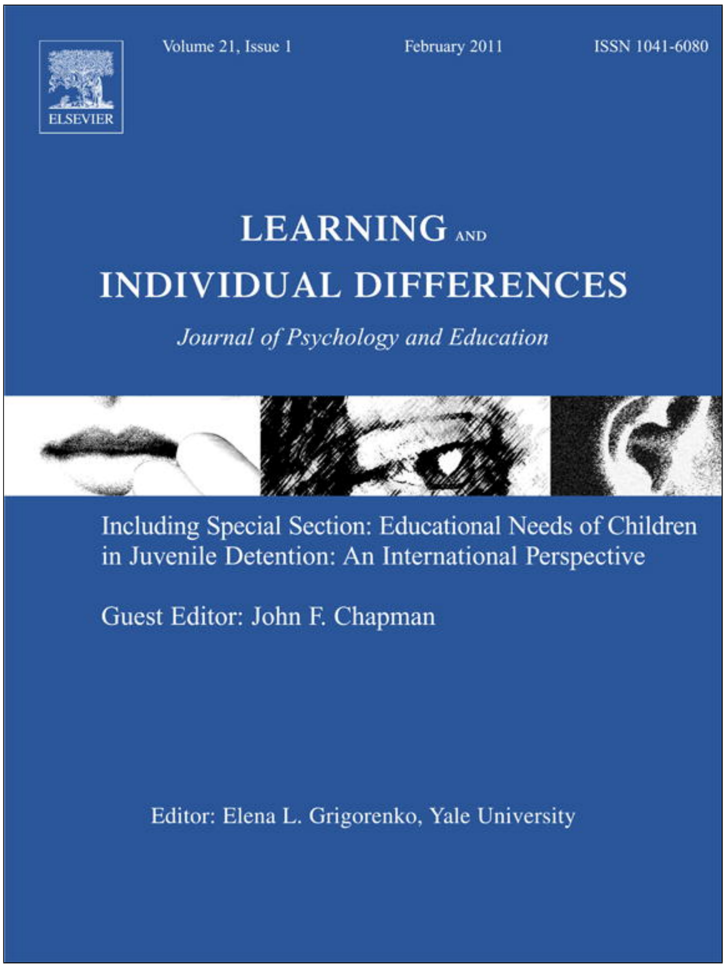
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# The relationship between working memory, IQ, and mathematical skills in children

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ABSTRACT

The aim of the present study was to investigate the contribution of working memory and verbal ability (measured by vocabulary) to mathematical skills in children. A sample of 206 seven- and eight-year-olds was administered tests of these cognitive skills. A different pattern emerged that was dependent on both the memory task and the math skill. In the seven-year olds, visuo-spatial and verbal memory uniquely predicted performance on the math tests; however, in the eight-year olds, only visuo-spatial short-term memory predicted math scores. Even when differences in vocabulary were statistically accounted, memory skills uniquely predicted mathematical skills and arithmetical abilities. This pattern of findings provides a useful starting point that can add to existing research on the contributions of working memory and vocabulary to different mathematical skills.



The main aim of the present study was to compare the contributions of working memory–the ability to process and remember information–and verbal ability (vocabulary) to mathematical skills. Baddeley's working memory model provides a useful framework for understanding the role of the different memory components in mathematical skills. The central executive is a domain-general component responsible for the control of attention and processing of information from long-term memory (Baddeley, Emslie, Kolodny, & Duncan, 1998). The temporary storage of information is mediated by the phonological loop for verbal material and the visuo-spatial sketchpad for visual and spatial representations (Baddeley & Logie, 1999). The fourth component, the episodic buffer, is responsible for binding information into integrated chunks (Baddeley, 2000). As measurement tasks have yet to be standardized for children, this component was not considered in the present study (but see Alloway, Gathercole, Willis, & Adams, 2004; Alloway & Gathercole, 2005, for the links between the episodic buffer and learning in children).

Although it is well-established that working memory is closely linked to mathematical skills, this relationship is mediated by the task as well as the child's age. Visuo-spatial memory (represented by the visuo-spatial sketchpad) functions as a mental blackboard to support number representation, such as place value and alignment in columns, in counting and arithmetic tasks (D'Amico & Guarnera, 2005; Geary, 1990; McLean & Hitch, 1999). Specific associations have also been reported between visuo-spatial memory and encoding in problems presented visually (Logie, Gilhooly, & Wynn, 1994; Trbovich & LeFevre, 2003), and in multi-digit operations (Heathcote, 1994). Visuo-spatial memory skills uniquely predict performance in nonverbal problems, such as sums presented with blocks, in pre-school children (Rasmussen & Bisanz, 2005), as well as problem-solving (Passolunghi & Mammarella, 2010).

Verbal short-term memory (represented by the phonological loop) has been linked to solving single-digit addition problems (Hecht, 2002; Seyler, Kirk, & Ashcraft, 2003) and maintaining operand and interim results in multi-digit problem (Fürst & Hitch, 2001; Heathcote, 1994; Noël, Désert, Aubrun, & Seron, 2001; Seitz & Schumann-Hengsteler, 2000, 2002). It is possible that verbal working memory (represented by the central executive in Baddeley's model) is a reliable indicator of mathematical disabilities in the first year of formal schooling (Gersten, Jordan, & Flojo, 2005; also Bull & Scerif, 2001), but not in older children (Reuhkala, 2001), as other factors, such as number knowledge and strategies, play a greater role (Thevenot & Oakhill, 2005).

The present study extends previous research by including a range of working memory measures. On the basis of the differential links between the memory components and arithmetical abilities, we included measures of verbal and visuo-spatial short-term memory and working memory (see Alloway, Gathercole, & Pickering, 2006; Bayliss, Jarrold, Gunn, & Baddeley, 2003; for support of this theoretical structure of working memory in development). This allowed us to systematically investigate the links between the various memory skills and mathematical skills and arithmetical abilities.

There is evidence that working memory tasks measure something different from general ability tests, such as IQ and vocabulary (Cain, Oakhill, & Bryant, 2004; Siegel, 1988). While these tests measure

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knowledge that the child has already learned, working memory tasks are a pure measure of a child's learning potential (Alloway & Alloway, 2010). Thus, working memory skills are able to predict a child's performance in learning outcomes, even after their general ability has been statistically accounted in reading and language skills (Gathercole, Alloway, Willis, & Adams, 2006; Nation, Adams, Bowyer-Crane, & Snowling, 1999; Passolunghi, Vercelloni, & Schadee, 2007; Stothard & Hulme, 1992; for a review see Swanson & Saez, 2003). The present study explored whether the same pattern of dissociation in the contributions of verbal ability, measured by vocabulary, and working memory would also be evident in tests that assessed a range of mathematical and arithmetic abilities.

Mathematical skills were measured by tasks involving ranking numbers, translating numbers from one representation to another (e.g., words to numbers), quantity discrimination, as well as more complex number skills, such as arithmetic computation (Butterworth, 2005). Also of interest was whether working memory and vocabulary would be differentially associated with mathematical skills as a function of age (Holmes & Adams, 2006; Passolunghi et al., 2007). For example, in the present study, verbal working memory may play a greater role in supporting arithmetical ability in younger children (7-year-olds), while visuo-spatial memory may be more closely linked to such skills in older children (8-year-olds) since some arithmetic tasks (e.g., more complex additions and subtractions) could require an elevated demand of visuo-spatial processing. The link between vocabulary and mathematical skills may be greater in the younger cohort as the individual is learning new information, rather than in the older group when gains made are likely the result of practice (see Jensen, 1980).

## 1. Method

### 1.1. Participants

There were 206 typically developing children (109 boys) recruited from four mainstream schools located in the north-west of Italy. The majority of parents came from professional homes that were predominantly middle class but included families from across the social spectrum. For the statistical analyses, participants were divided into two age groups: 7-year-olds ($n = 100$; $M = 88$ months, $SD = 3.5$ months; 50 boys) and 8-year-olds ($n = 106$; $M = 103$ months, $SD = 3.6$ months; 46 boys). None was receiving special education services or had documented brain injury, or behavioral problems. None of the assessed children belonged to families with socio-cultural disadvantage.

### 1.2. Measures

#### 1.2.1. Working memory

All 12 tests from the Automated Working Memory Assessment (AWMA, Alloway, 2007), a computer-based standardized battery that provides multiple assessments of verbal and visuo-spatial short-term memory, and of verbal and visuo-spatial working memory. There were three measures of verbal short-term memory where the child immediately recalls a sequence of information: digit recall, word recall, and nonword recall. Test–retest reliability is .89, .88, .69 for digit recall, word recall, and nonword recall respectively.

There were three verbal working memory measures: listening recall, backward digit recall, and counting recall. In the listening recall task, the child verifies a series of sentences by stating ‘true’ or ‘false’ and recalls the final word for each sentence in sequence. In the backwards digit recall task, the child recalls a sequence of spoken digits in the reverse order. In the counting recall task, the child counts the number of circles in an array and then recalls the tallies of circles. Test–retest reliability is .88, .84, .86 for listening recall, counting recall, and backward digit recall respectively.

Three measures of visuo-spatial short-term memory were administered. In the dot matrix task, the child is shown the position of a red dot in a series of four by four matrices and has to recall this position by tapping the squares on the computer screen. In the mazes memory task, the child is shown a maze with a red path drawn through it for three seconds. S/he then has to trace in the same path on a blank maze presented on the computer screen. In the block recall task, the child views a video of a series of blocks being tapped and reproduces the sequence in the correct order by tapping on a picture of the blocks. Test–retest reliability is .85, .86, .90 for dot matrix, mazes memory and block recall, respectively.

Three measures of visuo-spatial working memory were administered. In the odd-one-out task, the child views three shapes, each in a box presented in a row, and identifies the odd-one-out shape. At the end of each trial, the child recalls the location of each odd one out shape, in the correct order, by tapping the correct box on the screen. In the Mr. X task, the child is presented with a picture of two Mr. X figures. The child identifies whether the Mr. X with the blue hat is holding the ball in the same hand as the Mr. X with the yellow hat. The Mr. X with the blue hat may also be rotated. At the end of each trial, the child recalls the location of each ball in the blue Mr. X's hand in sequence by pointing to a picture with six compass points. In the spatial recall task, the child views a picture of two arbitrary shapes where the shape on the right has a red dot on it and identifies whether the shape on the right is the same or opposite of the shape on the left. The shape with the red dot may also be rotated. At the end of each trial, the child recalls the location of each red dot on the shape in sequence by pointing to a picture with three compass points. Test–retest reliability is .88, .84, .79 for the odd-one-out, Mr. X, and spatial recall, respectively. Raw scores for all tests are reported in the present study.

Test reliability of the English AWMA is reported here and test validity is reported in Alloway, Gathercole, Kirkwood, and Elliott (2008). The tests were translated and voice recorded into Italian by native speakers. As normative data for Italian is currently being collected, we report the intercorrelations between working memory composite scores in Table 1 based on the present sample. The between-construct coefficients were high ($r$s ranging from .35 to .66), suggesting good internal validity of the measures purportedly tapping four subcomponents of working memory. On this basis, the following analyses were based on the four memory components as reported in Alloway et al. (2006). The range of scores for all 12 memory tests is provided in Table 2 and the skewness and kurtosis values represent normal distributions for both age groups.

#### 1.2.2. Mathematical skills

All students were administered Italian AC-MT test, which consists of four tasks with different levels of difficulty depending on the age of the student (Cornoldi, Lucangeli, & Bellina, 2002). In the first task, Number Operations, the student solves basic operations such as single-digit addition (maximum score = 8). The second test measures Quantity Discrimination, and the student makes number comparison

**Table 1**
Correlations between all memory scores; partial correlations (controlling for age in months) in upper triangle ($n = 206$).

| Measures | VSTM | VWM | VS-STM | VS-WM | Vocabulary |
|---|---|---|---|---|---|
| Verbal short-term memory (VSTM) | 1 | .44 | .33 | .21 | .35 |
| Verbal working memory (VWM) | .50 | 1 | .50 | .50 | .36 |
| Visuo-spatial short-term memory (VS-STM) | .43 | .58 | 1 | .59 | .30 |
| Visuo-spatial working memory (VS-WM) | .32 | .57 | .68 | 1 | .33 |
| Vocabulary | .46 | .48 | .53 | .50 | 1 |

Note: All correlations are significant at the .005 level.

**Table 2**
Descriptive statistics of raw scores for cognitive measures as a function of age group (7 and 8 years).

| | | | | | 7 yrs | ($n=100$) | | | | | 8 yrs | ($n=154$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Skewness | Kurtosis | Mean | *SD* | Min | Max | Skewness | Kurtosis | Mean | *SD* |
| Memory tests | | | | | | | | | | | | |
| Digit recall | 16 | 32 | .260 | −.380 | 23.02 | 3.58 | 13 | 35 | −.303 | .800 | 25.22 | 3.55 |
| Word recall | 8 | 24 | −.678 | −.198 | 18.91 | 3.51 | 12 | 28 | −.759 | .423 | 20.29 | 3.20 |
| Nonword recall | 7 | 26 | −.318 | −.314 | 16.32 | 4.55 | 9 | 31 | .302 | .786 | 18.30 | 3.94 |
| Verbal STM | 12 | 26 | .171 | −.479 | 19.42 | 3.0 | 12 | 30 | 0 | .157 | 21.27 | 2.74 |
| Listening recall | 3 | 16 | .324 | −.364 | 8.57 | 2.77 | 5 | 18 | .416 | −.058 | 10.29 | 2.66 |
| Counting recall | 7 | 24 | .011 | −.133 | 15.01 | 3.72 | 6 | 25 | .370 | −.768 | 16.45 | 4.15 |
| Backward digit recall | 3 | 18 | .400 | −.018 | 9.69 | 2.93 | 6 | 28 | .111 | .897 | 11.31 | 3.71 |
| Verbal WM | 7 | 17 | .211 | −.175 | 11.09 | 2.24 | 7 | 21 | .549 | .274 | 12.69 | 2.65 |
| Dot matrix | 10 | 29 | .211 | .444 | 17.95 | 3.35 | 12 | 33 | .278 | .143 | 21.73 | 4.0 |
| Mazes memory | 5 | 26 | .206 | −.413 | 15.98 | 4.70 | 8 | 27 | −.911 | .083 | 20.14 | 4.67 |
| Block recall | 7 | 26 | −.300 | .177 | 17.47 | 3.91 | 11 | 33 | .176 | .262 | 20.50 | 4.16 |
| Visuo-spatial STM | 10 | 26 | .398 | .192 | 17.13 | 2.93 | 12 | 29 | −.132 | −.059 | 20.79 | 3.51 |
| Odd one out | 6 | 23 | .119 | .016 | 13.75 | 3.47 | 9 | 26 | .358 | −.135 | 15.90 | 3.53 |
| Mister X | 0 | 17 | .428 | −.479 | 7.47 | 3.72 | 1 | 19 | .284 | −.377 | 9.65 | 3.82 |
| Spatial recall | 0 | 23 | −.154 | −.439 | 11.18 | 4.84 | 1 | 24 | −.365 | −.032 | 14.00 | 4.28 |
| Visuo-spatial WM | 4 | 20 | .148 | −.369 | 10.80 | 3.19 | 6 | 19 | −.106 | −.642 | 13.18 | 3.03 |
| Number skills tests | | | | | | | | | | | | |
| Number Operations | 0 | 4 | | | 2.21 | 1.15 | 1 | 8 | | | 5.59 | 1.64 |
| Quantity discrimination | 1 | 6 | | | 5.38 | 1.22 | 0 | 6 | | | 5.42 | 1.16 |
| Number production | 0 | 6 | | | 3.60 | 1.63 | 0 | 6 | | | 5.58 | 1.02 |
| Number ranking | 0 | 11 | | | 8.36 | 2.44 | 1 | 11 | | | 8.78 | 1.83 |
| Arithmetic (WOND) | 1 | 12 | | | 10.18 | 1.66 | 12 | 22 | | | 19.10 | 2.23 |
| Vocabulary | 27 | 57 | | | 44.91 | 6.82 | 36 | 59 | | | 52.55 | 5.02 |

and identifies bigger and smaller numbers in a set (maximum score = 6). In the third test, Number Production, the student translates numbers from one representation to another (e.g., 4 dozen = 48; maximum score = 6). In the final test, Number Ranking, the student orders number sequences from the smaller to the higher and vice versa (maximum score = 11). The reliability is: Number Operations .74 (7 years) and .68 (8 years); Quantity Discrimination .69 (7 years) and .65 (8 years); number production .75 (7 years) and .72 (8 years); and .88 (7 & 8 years) for number ranking. The concurrent validity, reported in the AC-MT manual is also good: .84 (Cornoldi et al., 2002).

Arithmetical abilities were also assessed using the Numerical Operations subtest from the Wechsler Objective Numerical Dimensions (WOND, Wechsler, 1996). It consists of 10 four-item tests. The first set assesses the ability to write dictated numerals. The subsequent sets include computational problems addition, subtraction, multiplication and division. The correlation the Arithmetic subtest from the WOND and Number Operations test from the AC-MT is .42 (with age partialed out), which suggests that they assess different mathematical components. As with most standardized assessments, there is a discontinue rule, which means that not all sets were presented to the children in the present study and the younger children only completed a smaller number of sets compared to the older children. As there are currently no Italian standard scores are available for this standardized test, raw scores are reported in the present study.

*1.2.3. Vocabulary*

In order to assess general ability, the children were administered the PMA (Thurstone & Thurstone, 1968) vocabulary subtest, which consists of 60 items. In half the items, the child indicates which word has the same meaning as the target word. In the other half, the child indicates which picture corresponds to the target word. Raw scores were converted into standard scores, with a mean of 100 and a standard deviation of 15 based on an Italian sample. The test-reliability is .95. The correlations between vocabulary and the memory measures are provided in Table 1 and the partial correlation coeffiecients indicate a moderate association (*r*s ranging from .30 to .36).

## 2. Results

Descriptive statistics for the cognitive measures as a function of age-group are shown in Table 2. The following patterns emerged: the 7-year-olds scored lower than the 8-year-olds in all measures. In order to compare the working memory profile between age-groups, a MANOVCA was performed on the four memory composite scores, with age (in months) as a co-variate. The overall group term associated with Hotelling's *T*-test was not significant ($F > 1$, $\eta^2 p = .02$), suggesting that the memory profile did not differ significantly between the 7 and 8-year-olds once age was partialed out.

### *2.1. Working memory, vocabulary, and mathematical skills*

In order to investigate which memory component was linked to mathematical skills in 7 and 8-year olds, a series of stepwise regression analyses were conducted on the raw scores on the four sub-tests from the AC-MT and the Arithmetic subtest from the WOND. The vocabulary raw score and all four memory composite scores were entered simultaneously with a stepwise function. This approach allowed us to identify the best predictive variables for various mathematical skills as a function of age. Model statistics, as well as standardized beta values and t-statistics, are provided in Table 3.

For the 7-year olds, vocabulary accounted for significant proportion of variance (13%) across all mathematical skills: Quantity Discrimination (10%); Number Ranking (23%); Number Production (16%); Number Operations (12%); Arithmetic (13%). Of the four memory measures, visuo-spatial short-term memory accounted for significant additional variance to Quantity Discrimination (14%) and Number Production (21%). Verbal short-term memory accounted for significant additional variance in the Arithmetic test from the WOND (17%); and verbal working memory uniquely predicted Number Ranking (18%).

For the 8-year olds, vocabulary accounted for significant proportion of variance (13%) across some mathematical skills: Quantity Discrimination (9%); Number Ranking (30%); Number Operations (27%); Arithmetic (26%); but not Number Production. Of the four memory measures, only visuo-spatial short-term memory accounted for significant additional variance in predicting scores in Number

**Table 3**
Stepwise regression analyses predicting numerical skills as a function of age group.

| Dependant variables | Age group | | Independent variables | *R2* | *ΔR2* | *df* | *ΔF* | *B* | *t* |
|---|---|---|---|---|---|---|---|---|---|
| Quantity Discrimination (AC—MT) | 7 | 1 | Vocabulary | .10 | – | 1, 98 | 11.43 * | .32 | 3.38* |
| | | 2 | Visuo-spatial STM | .14 | .04 | 1, 97 | 4.84* | .21 | 2.12* |
| | 8 | 1 | Vocabulary | .09 | – | 1,104 | 10.44* | .30 | 3.23* |
| Number Ranking (AC-MT) | 7 | 1 | Verbal WM | .18 | – | 1, 98 | 21.53* | .42 | 4.64* |
| | | 2 | Vocabulary | .23 | .05 | 1, 97 | 6.87* | .25 | 2.62* |
| | 8 | 1 | Visuo-spatial STM | .23 | – | 1,104 | 31.15* | .48 | 5.58* |
| | | 2 | Vocabulary | .30 | .07 | 1,103 | 10.28* | .29 | 3.21* |
| Number Production (AC-MT) | 7 | 1 | Vocabulary | .16 | – | 1, 98 | 18.07* | .40 | 4.25* |
| | | 2 | Visuo-spatial STM | .21 | .05 | 1, 97 | 6.75* | .25 | 2.60* |
| | 8 | 1 | Visuo-spatial STM | .10 | – | 1,104 | 11.74* | .32 | 3.43* |
| Number Operations (AC-MT) | 7 | 1 | Vocabulary | .12 | – | 1,98 | 12.73* | .34 | 3.57* |
| | 8 | 1 | Visuo-spatial STM | .19 | – | 1,104 | 25.02* | .44 | 5.00* |
| | | 2 | Vocabulary | .27 | .08 | 1,103 | 10.72* | .30 | 3.27* |
| | | 3 | Verbal STM | .30 | .03 | 1,102 | 4.78* | .20 | 2.19* |
| Arithmetic (WOND) | 7 | 1 | Vocabulary | .13 | – | 1, 98 | 15.07* | .37 | 3.88* |
| | | 2 | Verbal STM | .17 | .04 | 1, 97 | 4.26* | .21 | 2.07* |
| | 8 | 1 | Vocabulary | .26 | – | 1,104 | 37.12* | .51 | 6.09* |
| | | 2 | Visuo-spatial STM | .35 | .09 | 1,103 | 14.41* | .33 | 3.80* |

Note: STM = short-term memory; WM = working memory; * $p<.05$; $B$ = standardized beta values.

Ranking (23%); Number Production (10%); Number Operations (19%); and Arithmetic test from the WOND (35%); but not Quantity Discrimination. Verbal short-term memory and working memory did not uniquely predict scores in any scores in the mathematical tests. The findings suggest an age-related difference in the contribution of memory to arithmetical abilities.

## 3. Discussion

The aim of the present study was to investigate the contributions of working memory and vocabulary to mathematical skills in children. The comparisons of the younger (7 years) and older (8 years) children showed slightly different patterns in the contribution of memory to mathematical skills and arithmetical abilities. Verbal memory predicted Number Ranking and Arithmetic skills in 7-year-olds, while visuo-spatial short-term memory predicted these same skills in 8-year olds. The latter also predicted performance in Quantity Discrimination and Number Production in the younger group.

In line with previous research, verbal short-term memory was an important predictor of performance in single-digit addition and subtraction problems (e.g., Hecht, 2002; Seyler et al., 2003). However, it did not predict scores in Number Operations, which may be due to the fewer number of items that the 7-year-olds solved (4 items). These items were also relatively easy and may have involved information that was automatically activated as a result of frequent repetition. Verbal working memory was uniquely linked to Number Ranking, which required the student to order number sequences from the smaller to the higher and vice versa. This task appeared to tap executive resources as they had to hold the items in mind while placing them in the correct numerical order.

The pattern of association between memory scores and mathematical skills was slightly different for the eight-year-olds. In particular, only visuo-spatial short-term memory accounted for significant additional variance in predicting the mathematical tests (except for Quantity Discrimination). The importance of visuo-spatial short-term memory fits well with evidence that it functions as a mental blackboard to support number representation particularly when problems are presented visually (Trbovich & LeFevre, 2003). One issue worth addressing is the unique contribution of visuo-spatial short-term memory, but not visuo-spatial working memory. One possibility is this age group (7–8 years) may have drawn more on executive resources when performing the visuo-spatial short-term memory tasks (see Alloway et al., 2006; Cowan et al., 2005). Inspection of the association between these two constructs for the present sample confirms that they share almost 50% of their variance, which is larger than any other of the memory constructs. Thus, given the close relationship between these two constructs, it is possible that the visuo-spatial short-memory tasks captured any additional variance of the visuo-spatial working memory ones.

Vocabulary scores uniquely predicted performance on all mathematical tests across the age groups, with the exception of Number Production in eight-year-olds. There was not an age-difference in the contribution of vocabulary to mathematical skills, which may be due to the nature of the math tests used in the present study. As the older cohort were presented with more items in some of the tests (e.g., Number Operations and Arithmetic) compared to the younger group, they were exposed to new information which likely tapped general ability. Indeed, the variance that the Vocabulary scores accounted for in both these math tests was twice as much for the older group. A key point is that short-term and working memory significantly predicted mathematical skills and arithmetical abilities after the variance associated with vocabulary was accounted, which indicates that working memory is not a proxy for intelligence and measures a dissociable cognitive construct (Gathercole et al., 2006; Passolunghi, Mammarella, & Altoè, 2008).

In summary, this exploratory study provides a useful starting point that can add to existing research on the contributions of working memory and vocabulary to different mathematical skills. A novel and significant finding was that even when differences in vocabulary were statistically accounted, memory skills uniquely predicted mathematical skills and arithmetical abilities. The pattern of findings reported in the present study can provide the first step of a series of subsequent investigations on underlying mechanisms related to mathematical skills, such as phonological processing skills (Hecht et al., 2001) and strategy use (Geary, Hamson, & Hoard, 2000).

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