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Paolo Stievano[1] – Davide M. Cammisuli[2] - Silvia Michetti[3]
Chiara Ceccolin[3] - Giovanni Anobile[4]

[1] *ASL Roma 2, Rome, Italy*

[2] *Department of Surgical, Medical, Molecular Pathology and Critical Care Medicine, University of Pisa, 2 Pisa, Italy*

[3] *ASL n. 12 Viareggio, Lucca, Italy*

[4] *Department of Developmental Neuroscience, Stella Maris Scientific Institute, Pisa, Italy*

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ABSTRACT

The aim of the present study is to determine the presence of specific and independent core processes involved in arithmetical skills. We evaluated performances of 68 typically developing school children (8-11 yrs) on numerosity acuity, number line, handwriting (non-math writing skills), phonemic and design fluency as well as math abilities. A principal component analysis on math subtests scores revealed three main factors: Numeracy, Magnitude and Handwriting. Correlations showed that phonemic fluency was associated with the Numeracy factor and the Magnitude factor while design fluency with the Handwriting factor. Number acuity was associated with the Magnitude factor, number line with the Numeracy factor, handwriting with the Handwriting factor. Hierarchical regressions analyses indicated that number acuity, number line, phonemic fluency and handwriting explained unique variance portions on Math test (factors scores). Our study suggests an explanation of the cognitive architecture of processes involved in arithmetical skills in school children.

Keywords: Mathematical learning; fluency; handwriting; mental number line; number acuity

1. Introduction

The mastery of numerical competence in early childhood, mainly based on a non symbolic system of numerical representation, becomes relevant for later cognitive and educational development (De Smedt, Noel, Gilmore, & Ansari, 2013; Piazza et al., 2010) predicting individual differences in mathematical achievement (Reigosa-Crespo et al., 2012).

Math learning is a complex and progressive process that encompasses a wide range of cognitive skills to be fulfilled. These skills may be classified as either general (e.g. working memory, attention) or specific ones (e.g. numberline and number acuity).

Furthermore, previous research suggests that mathematical abilities are subserved by “core” and “non-core” skills. Core skills are commonly regarded as the “innate” capacity to process numerical information, while non-core skills are those that are important for mathematical cognition, but are not exclusive to the mathematical domain, such as executive functions, spatial skills, and attention (Looi & Kadosh, 2016).

Core skills are those considered specialised for mathematical abilities, such as automaticity in processing numerical information, the ability to discriminate numerosities, represent numerosities and counting (Butterworth, 2010).

Non-core skills such as executive functions (EF) including inhibitory control and working memory (WM), spatial cognitive skills, and attention are important to mathematical abilities but are not exclusive to the mathematical domain. The contributions of non-core skills to mathematical abilities have been mainly established through correlational studies on the predictors of mathematical skills (Passolunghi & Lanfranchi, 2012).

Although there is much evidence that both skills play a fundamental role for math learning, the amount of research investigating their relative contribution is still insufficient to draw definitive conclusions. In particular, studies have not sufficiently defined the cognitive architecture of all the processes involved in mathematical learning and not clearly identified the specific role of core processes as essential in allowing arithmetical skills to function properly.

1.1 Number sense, number line and math skills

Numerical quantification, the preverbal ability to encode magnitudes is already functioning well before the acquisition of any formal number knowledge (Feigenson, Dehaene, & Spelke, 2004; Xu, 2003) and with similar evolutionary roots for human adults, infants and non-human primates (Cantlon, 2012; Feigenson, 2007): an “innate sense of number” (Dehaene, 2011). Numerosity (the cardinal value of a set) has been hypothesized to represent a primary perceptual attribute, directly perceptible (Anobile, Cicchini, & Burr, 2015; Burr & Ross, 2008; Cicchini, Anobile, & Burr, 2016) as well as the core of humans' preverbal math knowledge (Feigenson et al., 2004; Piazza et al., 2010).

Human infants use two different number systems: the Object-File System (OFS) and the Analogue Magnitude System or Approximate Number System (ANS). The OFS allows humans to precisely enumerate a small number of objects, usually N<4 (i.e. *subitizing*; Kaufman, Lord, Reese, & Volkmann, 1949), ANS instead encodes higher numerical ensembles (Dehaene, 2001; Feigenson et al., 2004; Sella, Berteletti, Martina, Lucangeli, & Zorzi, 2013). ANS is not errorless and obeys Weber's Law: errors linearly increase with numerosity. Weber Fraction, here, reflects the precision with which quantities can be estimated: an index of numerical acuity (Whalen, Gallisten, & Gelman, 1999). More recently, it has been suggested that three distinct systems could operate on different number ranges: *subitizing* (up to four stimuli), *numerosity estimation* (items greater then subitizing range but sparse enough to be discriminated as singles) and *texture-density* (packed stimuli crowding each other into a texture) (Anobile, Castaldi, Turi, Tinelli, & Burr, 2016; Cicchini et al., 2016). Such regimes have different features: *subitizing* is fast, errorless and attention-dependent. *Numerosity estimation* is a rapid but error-prone process (obeying Weber Law), eccentricity dependent (discrimination precision decrease as eccentricity increase) and little attentional based. At higher densities, *texture*-like mechanisms intervene; here, increasing numerosity thresholds do not remain constants (Weber's Law) but instead decrease (follow a square root law). A recent influential theory advanced the idea that ANS could reflect the ancient non-verbal substrate on which the later language based mathematical knowledge will build on throughout formal education (Piazza, 2010).

In line with this, it has been repeatedly shown that, at least in children, higher non-symbolic precision is associated with higher formal mathematical achievement (Anobile, Stievano, & Burr, 2013; De Smed et al., 2013; Piazza et al., 2010). A meta-analysis (Chen & Li, 2014) revealed a significant positive correlation between ANS and math performance (r = 0.20, 95% CI = [0.14, 0.26]) even when other cognitive abilities were checked for. With a similar strength, ANS also longitudinally (r = 0.24, 95% CI = [0.11, 0.37]) and retrospectively predicts children's math performance (r = 0.17, 95% CI = [0.07, 0.26]). Furthermore, children affected by math learning disabilities (e.g. development dyscalculia) also have poorer precision in estimating numerosity then age-matched peers (Mazzocco, Feigenson, & Halberda, 2011; Sella et al., 2013). Interestingly, numerosity, but not texture-density discrimination thresholds, correlates with math skills in children and adults (Tibber et al., 2013). Numerosity estimation constitutes a central part of mathematical achievement. It requires the integration of conceptual and procedural knowledge of numbers (Siegler & Booth, 2004) and it is important for different educational outcomes, such as mathematical proficiency, numerical processing and memory for numbers (Anobile et al., 2013; Lanfranchi, Berteletti, Torrisi, Vianello, & Zorzi, 2015). It has been suggested that individuals use a mental number line (Hubbard, Piazza, Pinel, & Dehaene, 2005) for mathematical tasks, such as numerosity estimation, that is influenced by children's understanding of the composition of Arabic number system in units, tens, etc. and some operations, such as retrieval of arithmetic facts and automatized ability related to numerosity (e.g. table, simple additions, subtractions, multiplications) (Moeller, Fischer, Nuerk, & Cress, 2015).

1.2 Fluency, handwriting and role of automation on learning

Two other specific cognitive abilities may relate to math achievement: fluency (verbal and not) as well as handwriting skills. Fluency, as an executive ability, requires generating appropriate novel responses (Lezak, 2004). Processing speed and phonological decoding (Fuchs et al., 2006) play a noteworthy role in mathematical skills.

Executive functions develop strongly in childhood and the order of computational strategies adopted to solve arithmetical tasks reflects its increasing maturity (Van der Ven, Kroesbergen, Boom, & Leseman, 2012). Previous research (Cragg & Gilmore, 2014; Viterbori, Usai, Traverso, & De Franchis, 2015) has pointed out different mathematical skills, by taking into consideration that executive functions differentially contribute to specific mathematical domains: number production, mental calculus and arithmetical problem-solving.

When children enter primary school, they have acquired preparatory skills as counting, that are predictive of mathematical proficiency (Toll, Van der Ven, Kroesbergen, & Van Luit, 2010). Counting strategies involve finger counting, making a drawing and counting the items, and counting out loud, that can be considered as arithmetical abilities sustained by fluency (Grimes, 2014). Subdomains of fluency include phonemic fluency (i.e., generation of words that start with a specific letter), ideational fluency (i.e., generation of uses for specific objects) and visuospatial fluency (i.e., generation of unique patterns) (Fernandez, Moroni, Carranza, Fabbro, & Lebowitz, 2009; Stievano & Scalisi, 2014). Fluency that underlies the triggering of a process or a direct action to achieve a goal with sufficient speed and accuracy, may play a role in handwriting skills. Intact generation abilities are a natural precursor to effective rule-governed behaviours and poor fluency skills may manifest themselves as repetitive behaviour, such as perseverations (Dichter, Lam, Turner-Brown, Holtzclaw, & Bodfish, 2009).

Handwriting is a complex activity in which there is a continuous interaction between lower-level perceptual-motor (e.g., motor planning, execution) processes and higher-level cognitive (e.g., psycholinguistic, executive function) processes (Abbott & Berninger, 1993; Graham & Weintraub, 1996; van Galen & Morasso, 1998). As low level motor processes become relatively automatic, there is concurrent activation of higher-level processes. Executive functioning is involved in the transcription phase with an emphasis on planning and organization in time and space (Rosenblum, 2013). In children with typical development, handwriting has been characterized by rapid quality improvement during grade 1 (age 6-7 years) that reaches a plateau by grade 2 (age 7-8 years); further improvements tend to be seen by grade 3 (age 8-9 years) when handwriting becomes automatic, organized and available as a tool to facilitate the expression of ideas (Feder & Majnemer, 2007).

Automation is extremely important for handwriting and other academic skills (e.g. reading, arithmetic) and if handwriting is not automatized, it results in a reduction in quality and quantity of a produced text (Connelly & Hurst, 2001; LaBerge & Samuels, 1974). The executive domains particular to handwriting include maintenance of information in working memory, the inhibition of predominant responses and the appropriate shifting and sustaining of attention for the purpose of goal-directed actions and visuospatial generativity (Blair, Zelazo, & Greenberg, 2005; Stievano, Michetti, McClintock, Levi, & Scalisi, 2016).

1.3 Aim of the study

The aim of the present study is to investigate the architecture of cognitive processes involved in arithmetical skills in primary school children and to determine specific and independent core processes. Particularly, we hypothesized that number acuity, number line, phonemic fluency and handwriting were involved in arithmetical skills as basic cognitive processes and concurred with mathematical achievement.

2. Methods

2.1 Sample

Sixty-eight (32 boys and 36 girls) typically developing children aged 8-11 years (mean age 9.7 yrs) participated in the study. Subjects were recruited from local schools and only those who returned a signed consent from parents were included. All the tasks were presented individually in a session of about 50 minutes by two psychologists involved in a 6-month training program at the

Public Health Unit 12 in Viareggio (Tuscany, Italy). The scoring was double-checked by psychologists and by research team leaders. All the tasks were administered in a standard order, as shown by the list below. The number of breaks was determined in order to minimize children's fatigue, alleviate difficulties and improve participation. None of the children was diagnosed as having specific learning disabilities or attentional disorders and all had non-verbal intelligence in the normal range, as measured by Raven's Coloured Progressive Matrices (Belacchi, Scalisi, Cannoni, & Cornoldi, 2008) as well as normal visual acuity, as measured by Snellen chart (Snellen, 1862).
Further statistical analysis of the same psychophysical and neuropsychological data already taken into consideration in a previous manuscript (Anobile et al., 2013) was carried out by particularly examining the role of independent and specific core processes in arithmetical skills.

2.2 Procedure

All visual stimuli were presented in a dimly lit room on a 17-inch LG touch screen monitor with 1280 × 1024 resolution at refresh rate of 60 Hz, viewed binocularly from 57 cm. Stimuli were generated and presented under Matlab 7.6 using PsychToolbox routines (Brainard, 1997).

2.2.1 Non-symbolic number processing

We choose to measure non-symbolic number processing by means of two non-symbolic tasks: numerosity discrimination and numberline. Even if both tasks require the processing of non-symbolic quantities, they may ask for different cognitive processes. In case of numerosity discrimination, participants are required to compare the numerical magnitude of two ensembles. The numberline task instead requires to first process the to-be-positioned numerosity and then to transform its magnitude into spatial coordinates related to the numerical range given by the numberline.

Indeed, in our previous study (Anobile et al., 2013) we found that non-symbolic numberline and numerosity discrimination were only slightly correlated. Furthermore, looking for correlation between them and math performance, we found that after controlling for age and non-verbal reasoning, only the correlation with numerosity discrimination remain significant (R^2 change = 5.3%, F change $_{(1, 64)}$ = 4.28, p = .043). In line with this, in a group of preterm children, has been recently found that, even if the performance on both tasks were not different from controls, numerosity discrimination and numberline performance were not correlated between them (Tinelli et al., 2015). These results suggest that, even if similar, non-symbolic number line and discrimination may rely on partially separate mechanisms.

2.2.2 Numerosity discrimination

Two patches of dots were briefly (500 ms) and simultaneously presented either side of central fixation. Children performed a comparison task indicating the side of the screen with more dots (by pressing the left or right arrow on a standard keyboard). Standard numerosity was fixed at 24 dots while the probe (of varying number) adaptively changed, according to subject responses, with numerosity determined by the QUEST algorithm (Watson & Pelli, 1983). The side of the standard and probe were counterbalanced. Patches consisted in non-overlapping dots (0.27° area) half white and half black, constrained to fall within a virtual circle of 6° visual angle. The procedure consisted of two blocks of 45 trials (90 trials in total). Each trial was initiated by the experimenter to ensure that children maintained fixation throughout. To ensure that neither density nor area were a consistent and reliable cue to numerosity, three different conditions were simultaneously interleaved: equal area (density and numerosity correlated), equal density (area and numerosity correlated) or a minimal increase in both. In the equal-area condition, area was kept constant at 6 degrees with density varying accordingly with numerical changes, while in the equal-density condition, density was fixed at 7.3% and area increased with numerosity accordingly. In the minimal-increase condition an increase in number was associated with half the equal-density condition increase in area and half the equal-area increase in density. The proportion of "more" trials were plotted against probe numerosity and fit with a cumulative Gaussian function where the 50% point provided an estimate of the point of subjective equality (PSE) and the normalized difference between this and the 75% point gave an estimate of Weber fraction (WF). WF is the discrimination threshold and could be conceptualized as the minimal notable changes, from the reference numerosity (24 in this case). For example, a WF of 0.25 means that, to be perceived as different form the reference (containing 24 dots), the probe stimulus need to have a minimal numerosity difference of 25% (± 6 dots in this case).

2.2.3 Mapping numerosity onto space

We measured the ability to map numbers using a ‘‘non-symbolic number line'' task. The task is similar to that already used by (Anobile et al., 2013; Cicchini et al., 2016; Tinelli et al., 2015). Subjects view a cloud of dots and position their quantity on a line demarcated by two sample numerosity. Each trial started with subjects viewing a 22 cm "number-line" with sample dot-clouds representing the extremes: one dot on the left of the number line, and 30 on the right, which remained throughout the trial. Dot stimuli were presented for 500 ms, followed by a random-noise mask that remained until the subject responded. The dots were half-white, half-black and positioned in pseudo-random positions on a grey background without overlap, within a virtual circle of 8° diameters. Subjects touched the touch screen at the position on the number line they thought corresponded to the dot cloud. Each block measured one of the 9 different numerosity that were each presented once in random order. Subjects performed three blocks, with numerosity of 2, 3, 4, 6, 10, 14, 18, 20 and 27. To discourage observers using strategies other than numerosity (such as texture density), on each block we kept constant either the total covered area (varying individual dot size) or individual dot size (varying total area covered), alternatively trial-by-trial. Thus on average, neither dot size nor total covered area correlated with numerosity. In the sample dot-clouds of the number line, we kept constant total covered area. It follows that the left extreme (numerosity of one) was represented by a dot with a diameter greater than the dots that represented the right extreme. We quantified performance by computing the root mean square error (RMS), an index that takes into account both *variance* (average standard deviation of trials at a particular numerosity) and *bias* (average distance of the mean response from the physical numerosity):

$$RMS = \frac{1}{N}\sqrt{\sum_{i}^{N}\left(\frac{X_i - R_i}{X_i}\right)^2}$$

where X_i is the tested numerosity on the *i*th trial, R_i is the response location to that numerosity and N is the number of trials.

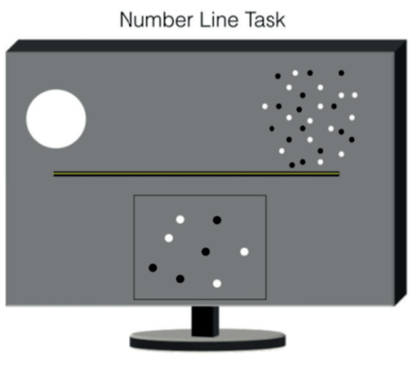

Figure 1. Numberline task: observers view a number line, marked at each end with a single dot to the left and 30 dots to the right. On key press, the dot stimulus appears, after 500 ms a binary pixel random-noise mask was displayed until subjects respond. Subjects touched the screen at the position on the numberline they thought corresponded to the dot cloud

2.2.4 Handwriting

Writing skills were assessed by the Handwriting Speed Test derived from a battery of measures for children between ages 7 and 13 years (Tressoldi & Cornoldi, 2000). The first part of the test (Handwriting T1) consisted of writing a continuous, repetitive and alternated sequence of cursive letters ("l" and "e") in a time interval (one minute) on a sheet of paper. The second part (Handwriting T2) involved writing "uno" as many times as possible within one minute. The third part (Handwriting T3) consisted of writing consecutive numbers in words (i.e., "one, two, three…"). The results of the Handwriting Speed Test were computed by the number of correct items written within the given time interval (1 minute per each task).

2.2.5 Phonemic Fluency

We decided to administer only one verbal fluency task, given that phonemic and semantic fluency measures are usually closely correlated (Filippetti & Allegri, 2011; Khalil, 2010). We chose the phonemic fluency (FP) (Bisiacchi, Cendron, Gugliotta, Tressoldi, & Vio, 2005) because it is more similar to the Five Point Test (see below), since both tasks use non-semantic material and assess functions related to activities in which the frontal lobe is more involved (Elfgren & Risberg, 1998; Warburton et al., 1996). Participants are asked to say, in three sessions of 60 seconds each, as many words as possible starting with a different letter in each session (C, P, and S). Derived words (i.e., words with the same prefix or suffix), repeated words, words that begin with a capital letter, and words that do not begin with the letters requested are regarded as errors. The accuracy score is the total number of correct words given in the three categories within the given time interval. The use of different letters as input is in line with many phonemic fluency tests used in other countries (cf. Filippetti & Allegri, 2011).

2.2.6 Design Fluency

The Five Point Test (FPT) is a nonverbal EF measure to assess design fluency (Regard, Strauss, & Knapp, 1982; Stievano & Scalisi, 2014). According to Suchy, Kraybill and Gidley Larson (2010), the test measures initiation, planning and divergent reasoning of an individual assessed by the production of unique geometric designs or figures within a short time period (i.e. 3 minutes). The test consists of a sheet of paper with 40, five-dot matrices. The test items appear on a sheet and are divided into unique squares. Five symmetrically arranged black dots are printed in each square. Participants are asked to produce as many different designs as possible by connecting the dots within each square with straight lines. The participants are instructed not to repeat designs (i.e., perseverative error) or draw lines that do not connect dots (i.e., rule break) (Albert, Opwis, & Regard, 2010). The final score consists of three indices: number of correct responses, perseverative errors and rule breaks. The number of correct responses (FPT Item) is an indicator for the ability to initiate and sustain mental productivity (Goebel, Fischer, Ferstl, & Mehdorn, 2009) while the number of rule break indicate mental inflexibility and poor planning. The qualitative analysis of production strategies can differentiate whether impaired performance is due to an initiation deficit or deficient planning abilities. The former tends to result in very few designs overall, and the latter results in more designs at the expense of more perseverative errors and lower planning scores (Goebel et al., 2009).

2.2.7 Math achievement

Mathematical achievement was measured by an age-standardized Italian Battery for Developmental Dyscalculia (BDE, Biancardi & Nicoletti, 2004) that explores several aspects of math with several different tasks in which accuracy and/or total time are recorded. There were ten separate tasks: 1. *Arabic numeral reading*: the child reads aloud 36 or 48 Arabic numbers – depending on chronological age – arranged in four different lists, each comprised of 12 integer numbers of three, four, five or six digits (e.g. 193, 1832, 31020, 142634). Both accuracy (total of numeral stated correctly) and speed were measured; 2. *Arabic numeral writing*: the child writes in Arabic format 36 or 48 spoken number words (3–6 digits, the same used for the numeral reading subtest) named by the experimenter, accuracy is measured; 3. *Arabic numeral repetition:* the child repeats 36 or 48 spoken number words of 3–6 digits (the same used for the numeral reading and *writing* subtests), and accuracy was measured (this subtest is not included in our research; most of the subjects performed this subtest without making mistakes); 4. *Triplets*: for 14 or 22 trials the child chooses the largest number among a set of three Arabic numbers (1–6 digits): both accuracy and speed were measured; 5. *Insertions*: for 12 trials the child positions a number (1–5 digits) in one of four possible positions among three other numbers: both accuracy and speed were measured. Triplets and insertions are collapsed together in a combined index called 'semantic coding'. Indeed, these tasks in order to be solved, requires to decode and manipulate the magnitude meaning associated with digits and are believed to tap the semantic component of numeracy (Biancardi & Nicoletti, 2004; Dehaene, Piazza, Pinel, & Cohen, 2003). 6. *Simple calculation*: the child performs 16 multiplications (operands between 1 and 9), 6 additions and 6 subtractions with results smaller than 10. A response is scored correct only if it was given within a 2 s deadline; 7. *Complex calculation*: the child performs 10 additions and 10 subtractions with results above 10. A response is scored as correct only if it was given within a 15 s deadline; 8. *Counting*: the child counts aloud between 1 and 100 in ascending and then descending order: both accuracy and speed are measured; 9. *Math tables*: the child recites aloud the 4 and 7 times multiplication table: response is scored correct only if there are no hesitations longer than 2 s; 10. *Complex written calculation*: the child performs 12 written calculations (4 additions, 4 subtractions, 4 multiplications within 10 minutes). The child is given a sheet of paper with the mathematical operations to be performed. The numbers on which to operate comprises integer Arabic numerals. Accuracy was scored. The scores were then age-standardized, to yield total math score (the sum of the individual scores). Because of reduced sample size (n.=68) we excluded some tasks of BDE (i.e. repetition, multiplication) from statistical analysis.

2.3 Statistical analysis

Descriptive statistics for all the measures were firstly performed. Successively, as data reduction analysis, a Principal Component Analysis (PCA) with oblimin rotation on the BDE math scores was carried out. We excluded from the analyses the scores of the Arabic numeral repetition task. This task was excluded mainly because it was highly positively correlated with the transcoding tasks (both number reading and writing) and thus bringing redundant information (see also Table 1 in Anobile et al., 2013). Given the relatively small sample size, in order to maximize the statistical power, we preferred to minimize the number of predictors.

A further correlation analysis was conducted between psychophysical and neuropsychological measures and factors scores from PCA, performing partial correlations (Pearson's *r*) controlled for age and non-verbal IQ. Finally, we investigated the unique contribution of the core processes in explaining additional significant variance to the dependent variables (factors scores on BDE) by four hierarchical multiple regressions. SPSS 23 software package was used to perform the statistical analyses.

3. Results

3.1 Descriptive analysis

Descriptive statistics of the total sample were first presented in Table 1.

3.2 Principal Component Analysis (PCA) to identify the main factors on math test scores

The Principal Component Analysis (Table 2) revealed three main factors with eigenvalues over 1, explaining together 67% of the variance. We termed the first factor 'Numeracy' as it collapses tasks mostly related to memory retrieval (e.g. math tables) and automatized competences (e.g. simple calculation) on numerical abilities (44% of variance). The second factor was termed 'Magnitude' (12% of variance) as it reflects competences related to number magnitude processing (e.g. complex calculation and digit magnitude comparison). The third factor was termed 'Numerical Transcoding' (11% of variance) and it is directly linked to transcoding (number reading, number writing, written calculation).

3.3 Correlation between math, psychophysical and neuropsychological variables

We reported Pearson's correlations between psychophysical and neuropsychological measures and scores of the three factors from ACP on the math scores extracted from the individual subtests, controlled for age and non-verbal IQ. High scores on math factor Numeracy were associated with less errors on the number line ($r = -.309$, $p < .05$) and better phonemic fluency performances ($r = .361$, $p < .01$). Magnitude factor positively correlated with number acuity ($r = .329$, $p < .01$), visuospatial reasoning ($r = .396$, $p < .01$), phonemic fluency ($r = .299$, $p < .05$) and Numeracy factor ($r = .409$), $p < .01$). Numerical Transcoding factor (mainly collapsing written math tasks) was associated with high scores on handwriting ($r = .306$, $p < .05$) and design fluency ($r =.241$, $p < .05$).

The principal component analysis on math scores revealed three main factors: Numeracy (collapsing memory retrieval and automatized competences), Magnitude (numerical magnitude processing) and Numerical Transcoding (Number reading, number writing, written calculation). The correlations showed that only some psychophysical and neuropsychological variables were associated to each factors identified. To identify the unique variance explained on math factors scores by specific cognitive processes (i.e., number line, phonemic fluency, number acuity and handwriting) we proceed with a hierarchical regression.

Table 1. Descriptive Statistics for All the Measures in the Total Sample (N= 68)

Measures	**M**	**SD**
Raven Matrices	26,76	4,156
Phonemic Fluency	20,66	6,875
Design Fluency	12,54	5,067
Counting	10,00	1,883
Number reading	9,00	3,407
Number writing	9,00	2,181
Semantic coding	10,04	1,838
Tables	9,75	1,450
Simple multiplication	9,16	1,872
Simple addition and subtraction	8,99	1,958
Complex addition and subtraction	9,24	1,884
Written calculation	9,96	2,121
Number line	,2501	,25594
Number acuity	,228	,0753
Handwriting	78,79	9,675

Table 2. Principal Component Analysis on the Math Scores Extracted from the Individual Subtests

	Rotate component matrix		
	Factor 1 (44%)	Factor 2 (12%)	Factor 3 (11%)
Measure	Numeracy	Magnitude	Numerical Transcoding
Tables	.891		
Simple multiplication	.768		
Simple addition and Subtraction	.665		
Counting		.837	
Semantic coding		.668	
Complex Addition and subtraction		.831	
Number reading			.731
Number writing			.758
Written calculation			.799

Note Proportion of variance accounted for by each factor and loading of each measure on factor

3.4 Hierarchical regression

In order to determine the unique contribution of the first hypothesized core processes, i.e. number line with regard to Numeracy factor, we performed a first hierarchical regression analysis. The results showed that Numerical Transcoding and Magnitude factors accounted for a significant 13.9% variance of Numeracy factor score (R^2 = .188, F = 5.384, p < .05) beyond the contribution of Raven Matrices. Number line accounted for a significant 5.6% variance of Numeracy factor score beyond the contributions of Raven Matrices (R^2 = .244, F = 4.672, p < .05), Numerical Transcoding and Magnitude factors. Number line is a non-symbolic number comparison according a psychophysical approach that taps into elementary numerical processes onto space. It can support higher-level numerical competencies like addition.

We then looked for the contribution of phonemic fluency with regard to the Numeracy factor and we ran a second hierarchical regression analysis. The results of this analysis showed that Numerical Transcoding and Magnitude factors accounted for a significant 13.9% variance of the Numeracy factor score (R^2 = .188, F = 5.384, p = 0.07 approaching significant) beyond the contribution of Raven Matrices. Phonemic fluency accounted for a significant 6% variance of the Numeracy factor score (R^2 = .247, F = 4.914, p < .05) beyond the contributions of Raven Matrices, Numerical Transcoding and Magnitude factors. This finding suggests that phonemic fluency supports the ability to make counting faster. Children start to acquire counting ability at preschool level and make it stronger at school level.

In order to determine the unique contribution of the Number acuity with regard to the Magnitude factor, we made a third hierarchical regression analysis. The results of this analysis showed that Numerical Transcoding and Numeracy factors accounted for a significant 11.6% variance of the Magnitude factor score (R^2 = .275, F = 4.972, p < .05) beyond the contribution of Raven Matrices. Number acuity accounted for a significant 4.2% variance of the Magnitude factor score (R^2 = .316, F = 3.717, p = 0.059 approaching significant) beyond the contributions of Raven Matrices, Numerical Transcoding and Numeracy factors. This finding suggests that an intuitive perception of numerical quantities, that does not depend on language or on other form of symbolic representation, has a critical role on numerical cognition abilities.

Finally, we were interested in determining the unique contribution of handwriting with regard to the Numerical Transcoding factor, thus we performed a fourth hierarchical regression analysis. The results of this analysis showed that handwriting accounted for a significant 8.9% variance of the Numerical Transcoding factor score (R^2 = .123, F = 3.951, p = .054 approaching significant) beyond the contributions of Raven Matrices, Numeracy and Magnitude factors. Such a kind of result implied the critical role of automatized writing skills for Numerical Transcoding factor as in other learning abilities linked to handwriting (e.g., written composition etc.).

4. Discussion

Our data are in line with previous investigations showing that number acuity and number line correlate with math skills (Anobile et al., 2013; Mazzocco et al., 2011; Piazza et al., 2010; Steele, Karmiloff-Smith, Cornish & Sherif, 2012) but describe the influence of other specific cognitive processes (fluencies and handwriting) for mathematical performances beyond the contribution of more general cognitive abilities previously investigated in other studies (i.e. visual working memory, visual attention, inhibition) (Mazzocco et al., 2011; Passolunghi, Cargnelutti, & Pastore, 2014).

With a PCA analysis on a math battery we detected three main factors: Numeracy, Magnitude and Numerical Transcoding. We then correlated these factors with psychophysical measures of numerosity acuity and neuropsychological measures of handwriting and fluencies (i.e., phonemic and design).

The Numeracy factor collapsed different tasks, such as the retrieval of the arithmetical facts and the automatized abilities related to numerosity (i.e. tables, simple multiplication, simple addition and subtraction). We found that this factor was related to phonemic fluency and distinguished by a specific ability (i.e., number line) that is not present in the other two factors. Phonemic fluency supports counting and the use of counting in solving problems, it is thus crucial for children's fluidity with numbers and reflects self-initiation. Moreover, the relationship between number line and mental calculation is in line with the idea that for mathematical operations such as addition and subtraction, individuals make access to a mental number line (Hubbard et al., 2005).

The Magnitude factor mainly summarizes those tasks involving the ability to perceive and manipulate digit numerical magnitude. We found that it was related to non verbal reasoning, phonemic fluency and distinguished by number acuity, that is not present in the other two factors. That Magnitude relates to number acuity is in line with previous studies with both typical children and children with low math achievement (Anobile et al., 2013; Piazza et al., 2010). Interestingly, despite the ability to perceive numerosity is largely generalized, integrating information across space (dots arrays), time (flashes and sounds streams) and even actions (finger tapping), children math skills only correlates with estimation of spatial numerosity (Anobile, Arrighi, Togoli, & Burr, 2016; Anobile et al., 2017; Arrighi, Togoli, & Burr, 2014). The parietal cortex (mainly intraparietal sulcus, IPS) is a good candidate to represent the brain area mediating this connection (Ansari & Dhital, 2006; Castaldi, Aagten-Murphy, Tosetti, Burr, & Morrone, 2016; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). A good amount of neuroimaging data showed functional and structural alterations of the IPS in children with mathematical learning disabilities (Dehaene, Molko, Cohen, & Wilson, 2004; Molko et al., 2003) and especially for those with developmental dyscalculia, thought to be a genetically determined disorder of number sense (Butterworth, 2010; Shalev, Unit, Zedek, & Berlin, 2007). More specifically, Rotzer et al. (2008) revealed that compared to controls, children with developmental dyscalculia have a significant reduction of gray matter volume in the right IPS, the anterior cingulum, the left frontal gyrus and the bilateral middle frontal gyri. Price, Halloway, Räsänen, Vesterinen and Ansari (2007) also demonstrated that in children with developmental dyscalculia, the right IPS is not modulated in response to numerical processing demands contrary to typically developing children.

We showed that Numeracy and Magnitude factors resulted correlated among them but independent from Numerical Transcoding (number reading, number writing and written calculation), too.

Finally, the Numerical Transcoding factor was significantly correlated with high scores on handwriting and design fluency. This may be explained by neuropsychological mechanism called '*energization*', that is the process of initiation and sustaining any response by which performance maintenance is ensured over time, linked to the activity of the upper medial circuit of prefrontal cortex (Stuss, 2011). *Energization* is connected to complete automated handwriting. Furthermore, a full maturation of executive functioning is the necessary foundation for successful handwriting both smooth and fast.

We investigated the architecture of some cognitive processes involved in arithmetical skills and the role of cognitive processes in math learning in a sample of typically developing children from 8-11 years of age. We found that Numeracy, Magnitude and Numerical Transcoding represent the three main factors summarizing different math tasks. Number acuity, number line, phonemic fluency and handwriting are clear-cut core processes explaining in a unique manner variance of these math factors, after the contribution of non-verbal IQ was accounted for. The contribution of the specific core processes for math learning can have important implications for education and rehabilitation trainings. In fact, the specificity of the processes involved in arithmetical tasks can lead health professionals to plan tailored interventions for children showing difficulties in mathematical learning. A specific assessment of the individual abilities of each child may contribute to a targeted rehabilitation strategy. The treatment of deficits should take into consideration both general cognitive abilities, such as attention and working memory and specific core processes, as those analysed in this study. In primary school education, a training coherent with these core processes should be presented continuously and instructively in order to build the basis for sustainable future mathematical learning (cf. Träff, 2013). Developmental Coordination Disorder (DCD) represents a clinical example that indicates the importance to consider all the variables analysed in our study. A recent study by Gomez, Piazza, Jobert, Dehaene and Huron (2016) suggest that children with DCD experience particular difficulties with mathematic learning. Other authors (Vaivre-Douret et al., 2011) reported that of 43 children with DCD, 38 (88%) showed academic underachievement in mathematics. According to Gomez et al. (2016), in children with DCD poor performance in arithmetic tasks could arise from a cascade of deficits: a fundamental impairment of non symbolic system of numerical representation may impair the representation of exact numbers which, in turn, would account for children's difficulties in calculation. Furthermore, in our study we examined the role of handwriting in arithmetical tasks: handwriting difficulties result to be very common in children with DCD, too (Rosenblum, Margieh, & Engel-Yeger, 2013). That the ability to perceive numerosity is tightly linked to the motor system also comes from studies on healthy adults. Indeed, has been recently found that after participants performed a high number of finger tapping movements, the numerosity of subsequent dots arrays and flashes streams is underestimated (and the opposite in case of few tapping actions) (Anobile et al., 2016).

The present study is limited by a relatively small sample size consisted of children with a typical development from 8 to 11 years of age. Further investigations should study in depth the role of the core processes at different age ranges, particularly in preschool children as well as in clinical populations (e.g. children with mathematical learning disabilities) to offer a more exhaustive explanation of their impact on arithmetical skills.

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