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Spatial Working Memory and Arithmetic Deficits in Children With Nonverbal Learning Difficulties

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Abstract

Visuospatial working memory and its involvement in arithmetic were examined in two groups of 7- to 11-year-olds: one comprising children described by teachers as displaying symptoms of nonverbal learning difficulties ($N = 21$), the other a control group without learning disabilities ($N = 21$). The two groups were matched for verbal abilities, age, gender, and sociocultural level. The children were presented with a visuospatial working memory battery of recognition tests involving visual, spatial-sequential and spatial-simultaneous processes, and two arithmetic tasks (number ordering and written calculations). The two groups were found to differ on some spatial tasks but not in the visual working memory tasks. On the arithmetic tasks, the children with nonverbal learning difficulties made more errors than controls in calculation and were slower in number ordering. A discriminant function analysis confirmed the crucial role of spatial-sequential working memory in distinguishing between the two groups. Results are discussed with reference to spatial working memory and arithmetic difficulties in nonverbal learning disabilities. Implications for the relationship between visuospatial working memory and arithmetic are also considered.

Keywords

visuospatial working memory, arithmetic, nonverbal learning disability

Nonverbal Learning Disability, Calculation, and Visuospatial Working Memory

Nonverbal (visuospatial) learning disability children are characterized by intact verbal abilities but impaired visuospatial abilities (Nichelli & Venneri, 1995; Rourke, 1989). In his research, Rourke (1989, 1995) specifically analyzed nonverbal learning disability children showing that their major problems lie in areas of spatial organizational, psychomotor, and nonverbal problem-solving skills within a context of well-developed psycholinguistic skills. According to Rourke, nonverbal learning disability children experience major academic learning difficulties in arithmetic, geometry, and science. Recent research has also demonstrated that these children display problems in analogical reasoning, namely, the processing and transfer of knowledge acquired in one situation or context to another (Schiff, Bauminger, & Toledo, 2009).

Nonverbal learning disability has also been associated with impairments of the right hemisphere. Nichelli and Venneri (1995) reported a case study of a 22-year-old man (AE) with a developmental learning disorder consisting of visuospatial deficits and arithmetic difficulties. In particular, AE made errors in writing multidigit numbers under dictation. In written calculation he gave incorrect answers arising through column confusion. Positron emission tomography scans revealed a marked hypo-metabolism of the right hemisphere. In a later study, Venneri, Cornoldi, and Garuti (2003), comparing nonverbal learning disabilities and controls in arithmetic calculations, found that the disabled group had more severe difficulties with written calculation, especially where this involved borrowing/carrying. The authors hypothesized that nonverbal learning disability children do not have a generalized problem with calculation per se; instead, their problems derive from dealing with specific processes, including visuospatial working memory (VSWM), that govern calculation.

There is increasing evidence showing the importance of VSWM in understanding the cognitive performance of

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nonverbal learning disability children (Cornoldi, Rigoni, Tressoldi, & Vio, 1999; I. C. Mammarella & Cornoldi, 2005a, 2005b). Difficulty in VSWM (which is involved in holding and manipulating visuospatial information) could explain the failures of these children not only in visual and spatial tasks clearly relying on VSWM, but also in motor coordination tasks (which have been shown to depend on the maintenance and manipulation of spatial information; Logie, 1995) and possibly in calculation tasks as well. Although recent research has shown that VSWM must be further differentiated (Cornoldi & Vecchi, 2003; Logie, 1995; Pickering, Gathercole, & Peaker, 1998), such differentiation has not undergone systematic study as regards nonverbal learning disability. In particular, with reference to the VSWM models proposed by Logie (1995), separation into visual and spatial subcomponents has been proposed. The former refers to recall of shapes and/or textures, the latter to recall of spatial locations and sequences. Furthermore, a number of studies (I. C. Mammarella, Pazzaglia, & Cornoldi, 2008; Lecerf & de Ribaupierre, 2005; Pazzaglia & Cornoldi, 1999; Rudkin, Pearson, & Logie, 2007) have differentiated between spatial-simultaneous working memory processes, referring to recall of locations presented simultaneously, and spatial-sequential working memory processes, in which participants have to recall spatial locations presented sequentially.

Differentiation within VSWM can help clarify conflicting data from the literature. In particular, some evidence suggests that nonverbal learning disability children are usually poorer in spatial tasks than in visual. For example, Cornoldi, Venneri, Marconato, Molin, and Montinari (2003) found that a group of such children, identified through a scale designed for school assessment (the *SVS Questionnaire*), were particularly poor in the spatial Corsi blocks task with an estimated size effect approximately double that found for two visual working memory tasks. Moreover, I. C. Mammarella et al. (2006) offered evidence supporting a double dissociation between spatial-sequential and spatial-simultaneous processes in children with nonverbal learning disability: Two of the three children described in the study showed selective impairment in spatial-simultaneous tasks, while the third displayed an opposite pattern of selective impairment in spatial-sequential tasks. However, there was no evidence of visual selective impairment in these children. Nonetheless, these cases were tested in VSWM tasks that also required executive processes, thereby excluding the possibility of testing specific VSWM components in nonverbal learning disabled children.

The Role of Visuospatial Working Memory in Arithmetic

Working memory (WM; Baddeley, 1986) is implicated in academic performance, including reading comprehension and mathematics (Swanson, 1994). Since Hitch's (1978) proposal that a "working storage" (part of the WM system) is used in arithmetic calculation for short-term retention of information related to both problem and solution, many studies have confirmed the critical role of WM in arithmetic. The central executive component (Baddeley, 1986) of WM—an attentional controlling system involved in coordinating performance on separate tasks—has been shown to play an important role in simple addition and multiplication (De Rammelaere, Stuyven, & Vandierendonck, 2001; De Rammelaere & Vandierendonck, 2001). The phonological loop, capable of maintaining and rehearsing verbal information, would be indispensable only in complex addition and multiplication (Fürst & Hitch, 2000; Seitz & Schumann-Hengsteler, 2000), not in simple cases (De Rammelaere et al., 1999, Seitz & Schumann-Hengsteler, 2002). Finally, although some studies have found no evidence for a role of VSWM in mental arithmetic (Logie, Gilhooly, & Wynn, 1994; Noël, Désert, Aubrun, & Seron, 2001), there is increasing evidence of its involvement in counting ability (Kyttälä, Aunio, Lehto, van Luit, & Hautamäki, 2003) and multidigit operations (Heathcote, 1994) in nonverbal problem solving (Rasmussen & Bisanz, 2005) and in mathematics ability in children aged 10 years (Maybery & Do, 2003) and 11 and 14 years (Jarvis & Gathercole, 2003). In a recent study, Bull, Espy, and Wiebe (2008) showed that VSWM specifically predicts mathematics achievement while executive function skills predicted learning in general rather than in one specific domain. Moreover, VSWM may be used when arithmetic operations are presented in specific modalities. Trbovich and LeFevre (2003; see also De Stefano & LeFevre, 2004) demonstrated that a phonological load impaired arithmetic performance when participants solved operations presented horizontally; in contrast, performance was worse using a visual load when participants solved operations presented vertically.

Regarding the WM deficits of individuals with mathematical difficulties (Passolunghi, & Pazzaglia, 2005; Passolunghi & Siegel, 2004), the results are no clearer than observed in experimental and typical developmental studies. Passolunghi and Siegel (2001) showed that children with a mathematics disability performed poorly on both numerical and verbal WM tasks. In contrast, Fletcher (1985) found that arithmetic disabled children were poorer in verbal than nonverbal memory tasks. Siegel and Ryan (1989) found that performance in children with a mathematics learning disability was impaired only on a WM task requiring processing of numerical information. Hitch and McAuley (1991) confirmed that children with specific difficulties in mathematics were impaired in WM tasks requiring the processing of numerical information but not in verbal WM tasks.

The relationship between arithmetic disabilities and working memory can vary according to the type of arithmetic disability involved (Butterworth, 2005). For example, Geary, Hoard, and Hamson (1999) studied a group of 7-year-olds at risk of a learning disability and found that mathematical failure was largely explained by different cognitive measures, including WM. Swanson and Beebe-Frankenberger (2004) found that first, second, and third graders with serious risk of mathematical difficulty performed poorer than children not at risk in a series of WM tasks. Studying a different group of 11-year-olds with learning disabilities, Swanson and Sachse-Lee (2001) found that problem-solving accuracy was predicted by both verbal and visuospatial WM.

Regarding the latter, children with specific mathematical difficulties are typically shown in studies to perform poorly on VSWM tasks (D'Amico & Guarnera, 2005; McLean & Hitch, 1999). It should be noted that one of the identified subtypes of mathematical learning disability includes individuals believed to have deficits in visuospatial skills, as suggested by Geary (1990, 1993, 2004); this is also confirmed by individuation of "spatial acalculia" in patients who have difficulties in considering the relative positions and order of digits (Hécaen Angerlergues & Houiller, 1961). Granà, Hofer, and Semenza (2006) described a single case of a patient who made errors previously described in relation to right hemisphere spatial acalculia, for example incorrect carrying in multiplication, omission of a digit on the left, omission of an additional line, and column confusion. These errors are examples of how visuospatial deficits might affect patterns of arithmetic difficulties but do not focus on specific aspects of spatial abilities. More specifically, since written arithmetic requires the maintenance and elaboration of numerical information displayed in space and analogical representation of quantities, a temporary spatial memory system may indeed be involved.

Overview of the Study

Summarizing the aforementioned findings, often derived from different approaches, it can be concluded that (a) nonverbal learning disability children often show arithmetic problems; (b) VSWM is impaired in nonverbal learning disability children, but their deficits can be related to specific VSWM subcomponents; (c) WM is involved in arithmetic; (d) VSWM is also involved to different extents in arithmetic, with respect to both age-specific effects and to different arithmetic tasks used; (e) there are suggestions of the existence of a visuospatial subtype of mathematic difficulty (Geary, 2004; Granà et al., 2006).

Although related, these aspects have never been studied together, research having focused mainly on mathematical difficulties using arithmetic difficulties as an identification criterion, thus excluding the possibility of studying them as dependent variables. We therefore used an alternative approach to examine VSWM and calculation. This involved systematic examination of the VSWM deficits of children with nonverbal learning difficulties and their related arithmetic difficulties, rather than analysis of VSWM failures in children with mathematical difficulties. Accordingly, we tested a group of children described by teachers as having symptoms of a nonverbal learning disability (hereafter "NLD group"), specifically with regard to their handling of visuospatial materials, and a matched control group. It should be emphasized that the children in our NLD group were not diagnosed as having nonverbal learning disability, but as displaying some of the symptoms as identified by their teachers.

To select the NLD group for the study, a series of problems had to be overcome: (a) A relatively large group of NLD children is needed for an adequate statistical survey, whereas very few children in Italy are diagnosed with a nonverbal learning disability. To obtain a clinical sample, it would have been necessary to contact a large number of learning disabilities centers. (b) These centers each employ different criteria for diagnosing nonverbal learning disabilities: This problem has been shown to be widespread, for example in interviews of clinicians conducted by Solodow et al. (2006). (c) Even where common criteria are adopted, procedures used for assessment are different and often also involve VSWM and arithmetic tasks. (d) In a study (such as the present one) devoted to examining weaknesses in VSWM and in arithmetic, nonverbal learning disability selection based on these tasks would not be correct, since it would imply circularity. (e) Children with diagnosis of nonverbal learning disability sometimes present a poor intellectual profile.

To overcome these problems we based the selection of our NLD on the *SVS Questionnaire* validated in two earlier studies on large samples of children (Cornoldi et al., 2003). The *SVS Questionnaire* specifically addresses the visuospatial disability category described by Forrest (2004), who suggested that NLD children can be categorized according to the nature of their underlying impairments. Specifically, he proposed a visual–spatial disability category for children with visuospatial deficits and a separate diagnostic category, namely, social processing disorders, for children whose social skill deficits are primary and impair everyday functions. Furthermore, the visuospatial score obtained with the *SVS Questionnaire* does not include items related to mathematical achievement or social skills: These symptoms do not always regard nonverbal learning disability children but instead aspects that are considered as potentially associated symptoms.

The main goals of the study were: (a) examine the failures of NLD children in VSWM and arithmetic tasks, to gain a better understanding of the difficulties encountered, and consider the implications of the relationship between arithmetic and VSWM; (b) identify which tasks in our study's battery are most reliable in discriminating NLD children from controls—as mentioned, the identification procedure for the NLD group is inconsistent and still under debate.

To examine VSWM aspects, passive simple-span tasks (Cornoldi & Vecchi, 2003) involving recognition were used—thus also eliminating operations implied in memory recall. Previous studies in the literature demonstrate that poor performance in active VSWM tasks also involving central executive processes is common in NLD, but studying this aspect does not allow analysis of the specific contribution of the VSWM components (Bull et al., 2008; Cornoldi, Dalla Vecchia, & Tressoldi, 1995).

For the arithmetic tasks, two were used that are considered to involve visuospatial processes, namely, written calculation and number ordering. In these tasks, visuospatial skills may affect the arithmetical processing at various levels: number inversions, misalignment of column digits, ignoring signs or changing operations, and borrowing and carrying errors. The visuospatial system also supports other aspects of nonverbal numerical processing involved in the tasks used, such as number magnitude, estimation, and representing information in spatial format, for example in a mental number line (Dehaene, 1997). The hypothesis was advanced that written calculation and number ordering tasks would be more difficult for NLD children, who usually have problems representing information using a spatial temporary system.

Method

Screening Phase

Participants and Selection Criteria

The initial sample involved 475 children (241 male, 234 female) aged 7 to 11 years. Specifically, 121 children attended second grade, 161 third grade, 107 fourth grade, and 86 fifth grade. The NLD children and the control group (CG) were identified on the basis of difficulties detected by their teachers through the *SVS Questionnaire* (Cornoldi et al., 2003).

The *SVS Questionnaire* is not a tool for diagnosing nonverbal learning disability, but is instead developed for its preliminary identification. Ten items on this questionnaire address some of the difficulties most often presented by nonverbal learning disability children at school and are used to obtain a basic visuospatial score (see appendix). This score has revealed high interrater agreement, ranging between .90 and .95 (Cornoldi et al., 2003), good test–retest reliability of $r = .76$ at one-year distance (Cornoldi et al., 2003), even higher ($r = .92$) for shorter intervals (Pedroni, Molin, & Cornoldi, 2007), and a good Cronbach alpha ($\alpha = .91$; see Cornoldi et al., 2003).

In a first study, Cornoldi et al. (2003) showed that an NLD group, reporting low visuospatial and high verbal SVS scores, was actually presenting neuropsychological symptoms typical of nonverbal learning disability. In a second study, Cornoldi et al., testing children with clinical diagnoses of either nonverbal learning disability or dyslexia, demonstrated that the *SVS Questionnaire* was capable of dissociating these two learning disabilities. The *SVS Questionnaire* therefore offers the possibility of wide-scale screening using the same criteria and procedures and eliminating problems associated with other procedures, in particular the circularity of selecting NLD on the basis of VSWM and arithmetic tasks. Moreover, in order to obtain a very specific group and avoid the confounding factor of a potential arithmetic deficit being due to an associated linguistic deficit—following the suggestion of Cornoldi et al.—children were included in the NLD group only if they had good verbal abilities as rated by their teachers.

Teachers were asked to evaluate whether a child presented a given characteristic on a 4-point scale. The *SVS Questionnaire* offers a visuospatial score based on 10 items (range: 10–40), validated for their sensitivity in detecting some of the deficits that represent critical features for nonverbal learning disability (Cornoldi et al., 2003). The questionnaire also includes two items used to obtain an indicative verbal learning score (range: 2–8) and one allowing a teacher's estimate of the child's sociocultural level (range: 1–4; 1 = *high sociocultural level*, 2 = *medium high*, 3 = *medium low*, 4 = *very low*). Children referred to as having a very low sociocultural level were not included in the groups, in order to avoid false positives. Only children who obtained visuospatial scores lower than 20th percentile and verbal scores greater than 50th were included in the NLD group. Using these criteria we were able to identify children with good verbal skills and poor visuospatial abilities. Raw scores were compared to the normative sample collected by Cornoldi et al. (2003), in which 4,026 children were tested using the SVS Questionnaire.

In the total sample 96 children obtained a visuospatial score lower than 20th percentile; 8 had a very low sociocultural level and were excluded. Of the remaining 88, only 21 also satisfied the verbal score criterion (greater than 50th percentile); these were recruited to the NLD group. In contrast, only children reporting scores equal to or greater than 50th percentile in *both* visuospatial and verbal scores were included in the CG: These children were selected in order to differ on just the visuospatial score and were matched for grade. The NLD (CG) groups included 4 (3) second graders, 13 (14) third graders, 3 (3) fourth graders, and 1 (1) fifth grader, with age, gender, verbal score, and sociocultural level as estimated by teachers.

In conclusion, the groups were different in visuospatial score, $t(40) = -15.87$ $p = .001$, but similar in verbal score, $t(40) = -.55$, $p = .58$, age $t(42) = -1.34$, $p = .19$, sociocultural level U Mann-Whitney = 199.5, $p = .15$, and gender $\chi^2(1, N = 42) = 1.61$, $p = .20$. Teachers also completed a questionnaire addressing symptoms of ADHD and the other most frequent developmental psychopathologies (including depressive, anxiety, and autistic symptoms): The two groups did not differ in either hyperactivity, $t(40) = -.14$, $p = .89$, or inattentive, $t(40) = -1.51$, $p = .14$, scores; nor did they differ in developmental psychopathology scores, $t(40) = 1.58$, $p = .12$.

Experimental Phase

Participants

The study consisted of the 21 NLD (15 male, 6 female) and the 21 CG (11 male, 10 female) participants as identified on the basis of the *SVS Questionnaire* (Cornoldi et al., 2003).

Materials and Procedure

Visuospatial working memory tests. Participants were presented with nine computerized tests, included in a VSWM test battery (I. C. Mammarella, Toso, Pazzaglia, & Cornoldi, 2008). In particular, three tasks involved visual passive processes, requiring recognition of shapes or textures; three tasks involved spatial-sequential processes, requiring the recognition of sequences of locations; and three others involved spatial-simultaneous processes, requiring the simultaneous recognition of presented locations (see Figure 1). The nine tests had the same structure. Children were asked to decide if a series of figures/locations were the same as or different from the one previously presented: In the tests, following a first stimulus presentation, either the same stimulus or one with a change of only one element was presented. This was followed by a response screen containing two letters U (*uguale* = same) and D (*diverso* = different): The child had to respond by pressing one of two keys on the keyboard. Before starting the experiment, the children spent a few minutes practicing to familiarize themselves with the two keys and ensure their function was clear.

For each test, half the items required a "same" response and half a "different" response. The tests progressed from the second (two stimuli) to the eighth (eight stimuli) level, with three items at each level. A self-terminating procedure was employed: Participants performed the tasks until they were able to solve at least two items out of three at a specific level. For scoring, items on the second level had a value of 2, those on the third level a value of 3, and so on; final scores were the sum of the last three correct responses. For example, if a child successfully solved two items on the fourth level and one on the fifth, then the score was 4 + 4 + 5 = 13. Before administration of each task, participants were given two practice trials with feedback. Tests were administered in a quiet room at the child's school during a single, individual session. In order to avoid biasing of performance in any test through effects of practice or fatigue, test presentation order was balanced.

Visual Tests

The nonsense shapes task. Children were presented with a series of two to eight nonsense figures and had to decide whether or not these figures were identical to the previous ones. At the second level two figures were presented, at the third three figures, and so on. At the beginning of the procedure a blank screen appeared for 1,000 milliseconds, followed by another blank screen for 500 milliseconds, and then the nonsense figures (3,000 milliseconds), followed by another blank screen for 500 milliseconds. After presentation of a fixation point for 1,500 milliseconds, either the same series of figures or a series differing in one figure was presented for the recognition task, followed by the response screen (U and D) as described previously: The child had to respond by pressing one of two keys on the keyboard.

The little fish recognition task. Participants were presented with series of two to eight fish, in which the fish shapes remained the same but the texture changed. Presentation times and other procedural aspects were the same as those for the non-sense shapes task.

The toy balloons recognition task. Participants had to recognize if textures inside balloons were the same or different. Presentation times and other procedural aspects were the same as those for the previous visual tasks.

Spatial-Sequential Tests

The sequential lightbulbs recognition task. In this task, a gray screen was presented for 1,000 milliseconds followed by a large circle composed of 12 small blank circles shown to participants for 250 milliseconds. Immediately afterward, one of the small circles was lit up (became yellow) for 1,000 seconds, followed by a 250-millisecond interval, and then another circle was lit up, and so on. The number of lit circles varied from two to eight, according to the complexity level. At the second level, two small circles were lit one at a time, at the third level three, and so on. After a delay of 500 milliseconds after the last circle was lit up, a fixation point of 1,000 milliseconds and another delay of 500 milliseconds, the same sequence or one with one small circle in a different order was presented at the same rate.

The sequential lines task. The stimuli were derived from Miyake, Friedman, Rettinger, Shah, and Hegarty (2001). Participants were presented with 5 × 5 matrices composed of 25 small black dots. The presentation times were identical to those of the previous task. The sequentially presented

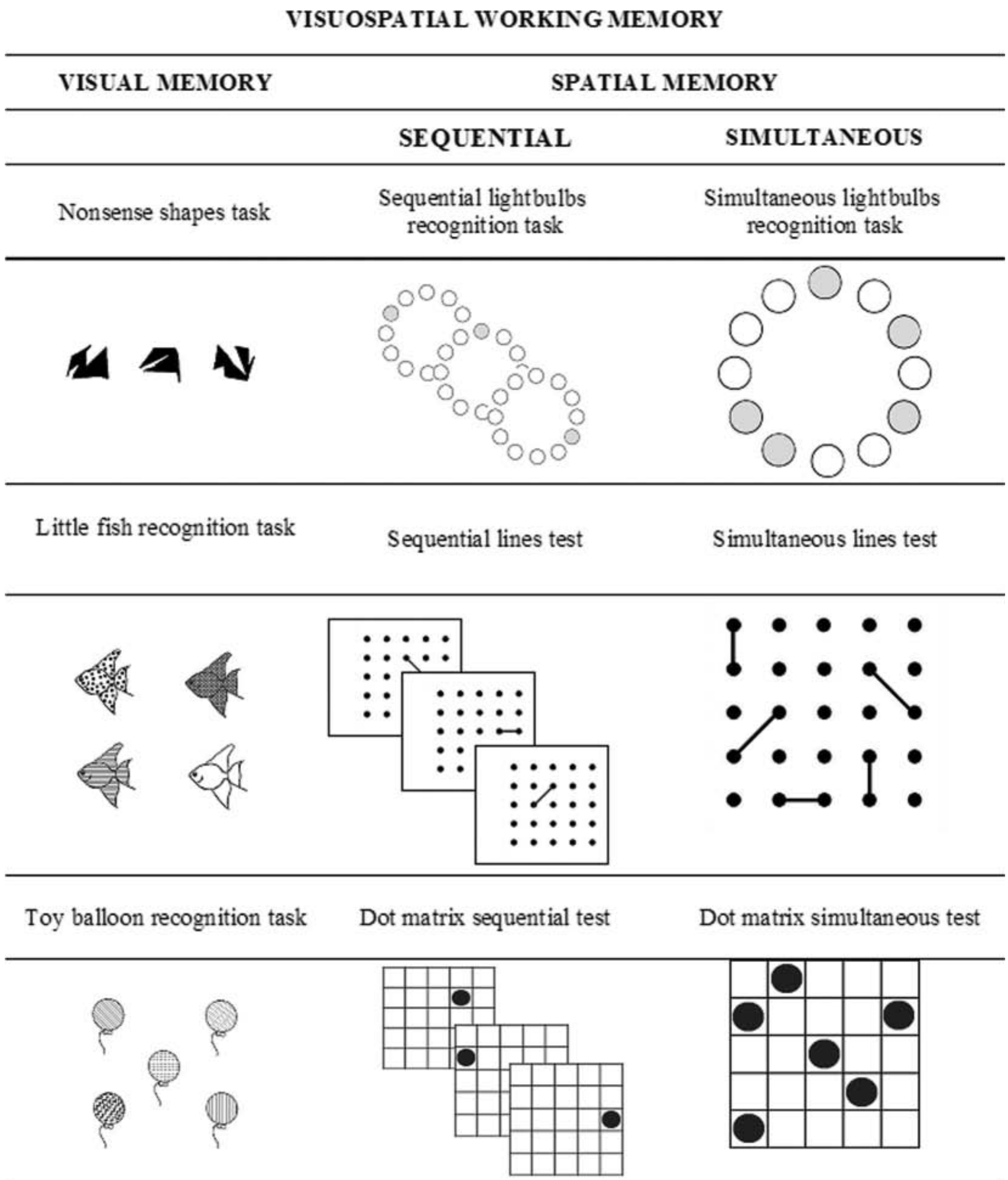

Figure 1. The nine measures of VSWM distinguished according to visual, spatial-sequential, and spatial-simultaneous subcomponents.

stimuli were black lines joining up the dots, appearing one at a time. Participants had to decide whether or not the sequentially presented lines were in the same order as those previously presented.

The sequential dot matrix task. The task involved 5 × 5 matrices in which red dots appeared one at a time, following the presentation times of the previous tasks. Participants had to decide whether or not the presentation order of the red dots was the same in the target and the recognition display.

Spatial-Simultaneous Tests

The simultaneous lightbulbs recognition task. The same display as that used in the sequential lightbulbs recognition task was used (12 small circles forming a large circle), but this time the small circles were all lit up (turned yellow) together. During the test, participants had to decide if the new pattern of yellow circles was the same as that just presented or whether one yellow circle appeared in a different location. After a gray screen of 1,000 milliseconds, a display of 12 small circles appeared for 500 milliseconds on the screen and then a variable number (depending on complexity level, from two to eight) of small circles were lit up for 2,500 milliseconds, followed by another delay of 500 milliseconds. After a fixation point of 1,000 milliseconds the presentation was repeated but with the lit yellow circle possibly in a different location.

The simultaneous lines task. The same 5 × 5 matrices as those employed in the sequential lines test were used. The only difference was that here the lines joining the dots appeared simultaneously and participants had to decide whether or not there was a line in a different location. Presentation times and other procedural aspects were the same as those for the simultaneous lightbulbs recognition task.

The simultaneous dot matrix task. Stimuli were the same as in the sequential dot matrix test but the red dots appeared simultaneously. Presentation times were identical to those for the previous simultaneous tests and participants had to decide if all the dots appeared in the same or in different locations.

Arithmetic Tasks

Children were presented with two arithmetical tasks (paper–pencil materials), controlled for difficulty (according to grade at school). The tasks specifically devised for the present study are given in the appendix.

Written calculation. Participants were given 18 written calculations: 9 additions and 9 multiplications. These were in random order and written horizontally on a blank sheet of paper (e.g., 541 + 1847, 5 × 52953). Participants were allowed a maximum of 10 minutes to write out the calculations in columns (this allowed calculation of the frequency of errors in this part of the task: "column confusion") and a maximum of 10 minutes to do the calculations themselves. In order to exclude a measure of accuracy being affected by omissions (i.e., the fact that a child did not try some of the calculations), the proportion of errors in doing the calculations (calculation errors) was considered, namely, the proportion of incorrectly solved operations based on the number of additions and multiplications the child actually attempted. Furthermore, the mean proportion of errors in performance of carrying in both addition and multiplication, the mean proportion of errors in interpreting the operation sign (i.e., when a child summed instead of multiplying, or vice versa), and the mean proportion of errors in computing partial results (e.g., 55 + 12 = 68) were considered. Finally, the mean times (in seconds) taken to write out the calculations in columns and perform them were calculated.

Number ordering. The task was split into two parts: ordering numbers from smallest to largest and from largest to smallest. The particular feature of the test was that for each series, the digits of the numbers were the same but arranged in different positions (e.g., 169, 691, 196, 961). Participants were presented with a set of cards on which a number was printed and had to put the cards in order. The frequency of errors and response time (in seconds) were measured.

Results

VSWM and Arithmetic Differences Between NLD and CG

The first goal of the study was to analyze the failures of NLD children on arithmetic and VSWM tasks and the relationship between arithmetic and VSWM.

Preliminary ANCOVAs—comparing the groups in all variables with age, gender, sociocultural level, hyperactivity, inattentive, and developmental psychopathology scores as covariates—showed that the covariate variables were never significant and did not change the pattern of results, demonstrating that the two samples were satisfactorily matched. For this reason, the aforementioned variables were not taken into account in the subsequent analyses. Descriptive statistics are reported in Table 1.

For VSWM, three mixed ANOVAs were performed, distinguishing between the three groups of VSWM tasks. A 2 (groups: NLD vs. CG) × 3 (visual tasks: nonsense shapes task vs. little fish recognition task vs. toy balloons recognition task) mixed ANOVA showed neither a main effect of group, $F(1, 40) < 1$, nor a main effect of visual tasks, $F(2, 80) = 1.47$, $MSE = 24.68$, $p = .24$, $\eta^2 = .04$. The interaction group by visual tasks was also not significant, $F(2, 80) < 1$. A 2 (groups: NLD vs. CG) × 3 (spatial-sequential tasks: sequential lightbulbs recognition task vs. sequential lines task vs. sequential dot matrix task) mixed ANOVA showed a main effect of group, $F(1, 40) = 15.44$, $MSE = 40.29$, $p < .001$, $\eta^2 = .28$, a result of the fact that CG participant mean performance (11.33) was better than that of the NLD group (6.89). The interaction group by spatial-sequential tasks was also significant, $F(2, 80) = 14.38$, $MSE = 25.68$, $p < .001$, $\eta^2_p = .26$. Post hoc analyses using Tukey's honestly significant difference (HSD) test revealed that the NLD group performed worse than the CG on both the sequential light bulbs recognition task ($p < .01$) and sequential dot matrix task ($p < .01$); however, there were no differences in the performances on the sequential lines task (see Table 1). Finally, a 2 (groups: NLD vs. CG) × 3 (spatial-simultaneous tasks: simultaneous light bulbs recognition task vs. simultaneous lines task vs. simultaneous dot matrix task) mixed ANOVA did not show a main effect of group, $F(1, 40) < 1$, but did show a main effect of the spatial-simultaneous tasks, $F(1, 40) = 10.96$, $MSE = 36.91$, $p < .001$, $\eta^2 = .22$. A post hoc comparison using Bonferroni's correction showed that both the simultaneous lightbulbs recognition task and the simultaneous dot matrix task were easier than the

Table 1. Descriptive Statistics of Visuospatial Working Memory (VSWM) Tasks, Mean Performances, Standard Deviations, Nonverbal Learning Disability Group (NLD), and Control Group (CG)

					NLD		CG	
VSWM Tasks	Reliability	Maximum Possible	Skewness	Kurtosis	*M*	*SD*	*M*	*SD*
Visual								
Non-sense shapes	.89	24	0.90	0.70	9.1	4.6	9.9	5.5
Little fish	.88	24	1.14	0.61	8.6	5.3	9.5	6.5
Toy balloons	.86	24	0.94	0.73	7.1	3.9	8.4	5.2
Spatial-sequential								
Sequential lightbulbs	.89	24	0.56	−1.01	4.3	5.1	14.1	5.7
Sequential lines	.87	24	0.46	0.03	9.6	4.9	7.7	5.4
Sequential dot matrix	.91	24	0.26	−1.16	6.7	5.4	12.2	6.4
Spatial-simultaneous								
Simultaneous lightbulbs	.88	24	−0.18	−1.04	14.4	6.3	14.4	7.8
Simultaneous lines	.85	24	−0.22	−0.76	9.6	4.2	7.9	4.8
Simultaneous dot matrix	.90	24	0.08	−0.83	11.2	7.4	16.3	5.3

simultaneous lines task ($p < .001$ in both cases). Moreover, the interaction group by spatial-simultaneous tasks was significant, $F(2, 80) = 3.57$, $MSE = 36.91$, $p < .05$, $\eta^{2p} = .08$. Post hoc analyses using Tukey HSD test revealed that NLD and CG were only different in the simultaneous dot matrix task ($p < .01$).

As the results had shown a heterogeneous pattern of differences between groups within the two categories of spatial tasks, we performed Pearson's correlations. Concerning the three sequential tasks, the analysis revealed a good correlation between sequential lightbulbs and sequential dot matrix ($r = .52$); on the contrary the sequential lines test did not correlate with either the sequential lightbulbs ($r = .06$) or the sequential dot matrix ($r = .05$). The same pattern was observed, calculating separate correlations for each group. For the spatial-simultaneous tasks, Pearson's correlations revealed that the simultaneous dot matrix task (the only one in which differences between the groups were observed) did not strongly correlate with either the simultaneous lightbulbs ($r = .18$) or the simultaneous lines task ($r = .11$); moreover, the simultaneous lines and simultaneous lightbulbs tasks did not correlate either ($r = .10$) and the same pattern was observed performing separate correlations between groups.

For the arithmetic tasks, nonparametric statistical analyses for column confusion and frequency of number ordering errors were carried out. NLD and CG were found to differ in frequency of column confusions, $\chi^2(1, N = 42) = 10.71$, $p = .001$ (NLD = 57.1%, CG = 9.5%), whereas the two groups did not differ in frequency of number ordering errors.

A MANOVA was performed to compare the two groups in the following variables: mean proportion of errors in calculations, omissions (i.e., operations the child did not attempt), mean proportion of errors in carrying, mean proportion of errors in computing partial results, mean proportion of errors in interpreting the operation sign, calculation times (i.e., mean times in writing and solving calculations), and number ordering times.

The main effect of group was significant, $F(7, 34) = 2.57$, $p = .03$, $\eta^{2p} = .35$. To improve interpretation of this result, univariate tests of significance were considered. Significant differences in the mean proportion of errors in calculations were observed, $F(1, 40) = 11.11$, $p = .002$, $\eta^2_p = .22$ (NLD = .46, CG = .22). However, omissions were not significantly different between NLD and CG, $F(1, 40) = .85$, $p = .36$, $\eta^2_p = .02$ (NLD = 3.38, CG = 2.19). The groups differed in carrying errors, $F(1, 40) = 4.27$, $p = .04$, $\eta^2 = .10$ (NLD = .12, CG = .06), and in computing partial results, $F(1, 40) = 9.49$, $p = .004$, $\eta^2 = .19$ (NLD = .26, CG = .11). The mean proportion of errors in interpreting the operation sign was far from significance, $F(1, 40) < 1$, $\eta^2 = .005$ (NLD = .046, CG = .035).

Finally, no differences were observed in the calculation times, $F(1, 40) = 1.96$, $p = .17$, $\eta^{2p} = .05$ (NLD = 359.38 seconds, CG = 402.52 seconds). In contrast, significant differences in the number ordering times were observed, $F(1, 40) = 6.86$, $p = .012$, $\eta^{2p} = .15$ (NLD = 49.92 seconds, CG = 30.54 seconds).

Although the study design precluded direct examination of the relationship between VSWM and arithmetic, we examined the effect of VSWM on arithmetic scores in the two groups using ANCOVAs. Specifically, we compared the arithmetic performance of the two groups with ANCOVAs considering the VSWM tasks that showed group differences as covariates (see Note 1).

When groups were compared for number ordering times, with the sequential lightbulbs recognition task as covariate, the difference between groups was no longer significant,

$F(1, 39) = 3.43$, $p = .07$ ($R^2 = .15$, $\beta = -.05$, $p = .95$); similarly, using the sequential dot matrix as covariate, the difference between groups was no longer significant, $F(1, 39) = 2.32$, $p = .14$ ($R^2 =.17$, $\beta = -.62$, $p = .64$); finally, also using the simultaneous dot matrix as covariate, the difference between groups was no longer significant, $F(1, 39) = 2.94$, $p = .09$ ($R^2 = .24$, $\beta = -1.26$, $p = .03$). Concerning calculation errors, the significant difference between groups disappeared when the covariate was the sequential lightbulbs task, $F(1, 39) = 3.02$, $p = .09$ ($R^2 = .24$, $\beta = -.007$, $p = .29$); whereas the difference was still significant using both the sequential dot matrix as covariate, $F(1, 39) = 7.08$, $p = .01$ ($R^2 = .23$, $\beta = -.005$, $p = .44$), and the simultaneous dot matrix as covariate, $F(1, 39) = 6.63$, $p = .01$ ($R^2 = .26$, $\beta = -.008$, $p = .15$).

Discriminant Function Analysis

Addressing the study's second goal, to find tasks within our battery with highest discriminative power in distinguishing between CG and NLD children, a discriminant analysis was performed to identify the variables most capable of making this distinction and to predict the probability of a participant belonging to one particular group. It is worth noting that in the discriminant function analysis, column alignment and number ordering errors could not be included, since these were category variables. Before conducting the discriminant function analysis, issues related to sample size, multivariate normality, and multicollinearity were addressed (Tabachnick & Fidell, 1996). The criterion that the sample size of the smallest group should exceed the number of predictors was met. Group size was equal, ensuring multivariate normality. The discriminant function analysis was carried out with the stepwise method, using the nine VSWM tasks and the arithmetic measures. Box's M statistic was not significant ($p > .58$), indicating that the homogeneity of variance assumption was met. The only test included in the analysis was the sequential lightbulbs recognition task, Wilks's λ (Lambda) = .54, indicating that this was the variable best separating the two groups. The discriminant function analysis had a reliable association with NLD and CG, $\chi^2(1) = 24.37$, $p < .001$. The sequential lightbulbs recognition task alone was able to correctly classify into groups 90.5% of NLD children (i.e., 19/21) and 81% of CG children (i.e., 17/21).

Discussion

The relationship between VSWM and arithmetic was analyzed as a contribution to the study's main goal of examining VSWM and arithmetic failures in NLD children. This was approached by administering VSWM and arithmetic tasks to NLD children matched with controls for age, grade, gender, verbal abilities, and sociocultural level, rather than attempting direct analysis of VSWM failure in children with mathematics difficulties.

As noted earlier, participating NLD children had not been diagnosed as having nonverbal learning disability but showed some of the symptoms, specifically in dealing with visuospatial materials, typically associated with Forrest's (2004) visual-spatial disability category of nonverbal learning disability.

On the VSWM testing, NLD failed in two spatial-sequential tasks (sequential lightbulbs and sequential dot matrix) and in one spatial-simultaneous task (simultaneous dot matrix). This demonstrates that a VSWM deficit can also be found in NLD children in recognition tasks, namely, passive tasks typically less powerful than active tasks in discriminating between groups, but more specific in distinguishing between different VSWM components (Cornoldi et al., 1995; Cornoldi & Vecchi, 2003) and in predicting specific learning domain difficulties (Bull et al., 2008).

In particular, NLD children performed significantly worse in spatial (both -sequential and -simultaneous) than in visual tasks, confirming previous suggestions (e.g., Cornoldi et al., 2003). This result cannot be attributed to the spatial tasks being more difficult, since an opposite pattern has been observed, with similar tasks, in children with spina bifida (N. Mammarella, Cornoldi, & Donadello, 2003) and in Down syndrome children compared with Williams syndrome children (Vicari, Bellucci, & Carlesimo, 2006). However, our pattern of results showed that NLD children did not fail in all -sequential and -simultaneous tasks and that—more generally—the inclusion of three tasks within a same category of spatial-sequential tasks and of other three tasks within a same category of spatial-simultaneous tasks only offered an approximate description of the complex articulation of VSWM. In fact, the tasks included in the same category offered partly different outcomes, suggesting that their grouping in three categories, although supported by previous evidence (I. C. Mammarella et al., 2006, 2008), should be viewed with caution.

In particular, for the spatial-sequential tasks, NLD children did not differ from CG children in the sequential lines test. The specific characteristics of the latter task were further supported by the correlational analysis showing good correlation between sequential lightbulbs and sequential dot matrix tasks, but no correlation between these two tasks and the sequential lines test. The finding that NLD children did not fail in the sequential lines test seems to hinge on the specific strategy used by children, focusing on the shapes drawn out by the lines joining the locations rather than on the locations per se. In fact, the task was included in the groups of spatial-sequential tasks although we are aware that it could also involve visual processes since it immediately evokes possible shapes. Regarding spatial-simultaneous tasks, NLD and CG differed only in the simultaneous dot matrix. ANOVA results demonstrated that the simultaneous lines task was the most difficult test for both groups. Pearson's correlations revealed that this latter task did not correlate with either the simultaneous lightbulbs or the simultaneous dot matrix task. Furthermore, inclusion of this task as a covariate was not able to eliminate all the differences between groups in arithmetic. The weaker difference observed between groups in the spatial-simultaneous tasks could be partly due to the heterogeneity of the implied processes, but—in our opinion—it is also related to the nature of spatial-simultaneous processes. In fact, according to the Cornoldi and Vecchi (2003) model, the spatial-simultaneous process is intermediate between the spatial-sequential process (spatial-simultaneous tasks require maintenance of locations) and the visual process (since simultaneous presentation of locations could suggest a shape). In fact, some authors have classified spatial-simultaneous tasks as visual (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Logie & Pearson, 1997). These results thus are in line with the continuum hypothesis of Cornoldi and Vecchi (2003), ranging from spatial-sequential, through spatial-simultaneous, to visual component.

Our study also showed failures of NLD children in arithmetic, indirectly supporting the existence of a relationship between VSWM and arithmetic achievement (Bull et al., 2008; Rasmussen & Bisanz, 2005). In the psychology literature, the role of VSWM in arithmetic is still controversial, some studies failing to find evidence for a role of VSWM components in mental arithmetic (Logie et al., 1994; Noël et al., 2001), but others demonstrating involvement of VSWM in arithmetic (Bull et al., 2008; De Stefano & LeFevre, 2004; Holmes & Adams, 2006; Trbovich & LeFevre, 2003). The relationship between numbers and visuospatial representations was postulated earlier by Dehaene (1992), who hypothesized an analog code where numbers are represented as variable distributions of local activation along a mental number line. Moreover, examination of the literature on neuropsychological deficits in adults clearly reveals that VSWM and spatial abilities are relevant for performance in mathematics (Granà et al., 2006; Zorzi, Priftis, & Umiltà, 2002). Neuroimaging studies have suggested that VSWM and arithmetic involve both different and common brain areas. Zago and Tzourio-Mazoyer (2002), using positron emission tomography, showed that some areas in the parietal cortex (in particular superior bilateral parietal areas) were shared by the two tasks; however, calculation tasks also elicited activation in the left inferior parietal lobule and left precuneus. It should be noted that our study examined fairly young children, in whom arithmetic is unlikely to involve automatic processes, compared to older individuals, calculation processes are more likely to rely strongly on other cognitive systems, including VSWM (Holmes & Adams, 2006; Jordan, Hanich, & Kaplan, 2003).

Our results showed that NLD children made arithmetic errors typically associated with visuospatial processes, namely, carrying errors, partial calculation, and column confusion. Written calculation requires correct sequential organization of material and procedures, and ANCOVA results suggested that these errors might relate mainly to the spatial-sequential WM component. Moreover, NLD children were slower than CG in number ordering. In this case, the ANCOVAs suggested that both -sequential and -simultaneous components of VSWM might be critical, presumably because it supports the request for simultaneously processing and maintaining the different digits and numbers and comparing them sequentially. In fact, our covariance analyses confirmed that when the contribution of just one of the VSWM tests differentiating the groups was eliminated, the difference in number ordering times between groups also disappeared; similarly, when the contribution of the sequential lightbulbs recognition task was eliminated, the difference in calculation errors also disappeared. Our results thus confirm that an arithmetic difficulty is typically associated with NLD, but also suggest that a VSWM difficulty may be primary, offering further support to the assumption that spatial processes are critical for some aspects of numerical cognition. The pattern of results found here is consistent with previous evidence on NLD (Nichelli & Venneri, 1995; Rourke, 1989, 1995; Venneri et al., 2003). Studies in the literature have distinguished between two different types of visuospatial process involved in arithmetic. One concerns the conceptual referent on mental representation of quantities and numbers, for example, the analogical representation of quantities (e.g., Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Meck & Church, 1983). The other involves specific representation modalities (e.g., dots, verbal expression, and written symbols), in particular the identification of position and order of written symbols as addressed in our study. NLD children did not seem to have difficulties with the conceptual referent of quantities and numbers given that, in terms of accuracy, they performed as well as the CG in number ordering.

More specifically, our results confirm that an arithmetic difficulty may be associated with NLD, but also suggest that a VSWM difficulty may be primary in NLD. Taking up this point, our study concluded by exploring whether there were any specific VSWM and/or arithmetic tasks able to contribute to identification of NLD children. The discriminant function analysis demonstrated that the sequential lightbulbs recognition task was the instrument most useful in this sense: Using this VSWM task, 90% of the sample's NLD were correctly classified, confirming that in general, assessment of VSWM is crucial for analysis of NLD children. Thus, results from the discriminant function analysis strengthened the hypothesis that VSWM difficulty is primary in explaining NLD performance. In fact, our research demonstrates that in general, NLD children performed worse than CG on spatial WM tasks (both -sequential and -simultaneous) and that the sequential lightbulbs recognition task is a successful test for the spatial-sequential component of WM and appropriate for identifying NLD children. Finally, the fact that NLD children, with good verbal abilities, performed poorly in both VSWM and arithmetic tasks and that some VSWM tasks affected arithmetic performance lends further support to the hypothesis that VSWM is involved in arithmetic. However, further research is needed to confirm and extend the present results, by considering the specific contribution of visual, spatial-sequential, and spatial-simultaneous WM tasks in explaining the specific arithmetic failures of the nonverbal learning disabled.

Before reaching unequivocal conclusions from these results, further evidence is needed, and a number of critical issues must be considered. First, according to some authors (Forrest, 2004; I. C. Mammarella et al., 2006), the NLD population includes various different subtypes: These are associated to various neurological disorders that may be related to nonverbal disability (Rourke, 2000). Second, although confounding variables between the two groups were carefully controlled for, matching each aspect apart from the visuospatial score as referred by teachers, the selection procedure may have influenced the pattern of results. Focusing on the NLD children identified by the *SVS Questionnaire* (Cornoldi et al., 2003) avoided the risk of circularity in using neuropsychological tests for both identifying and testing children. The *SVS Questionnaire* is not an instrument for diagnosing nonverbal learning disability, but instead useful in screening for preliminary identification of visuospatial symptoms in NLD children. Third, both groups were in some respects high performers and thus our NLD children cannot be considered as representative of the most severe nonverbal learning disabilities.

In conclusion, NLD children are shown to fail specifically in spatial WM tasks, but not in visual WM tasks, and to make errors in calculations involving visuospatial processing, namely, carrying and aligning numbers in columns. Moreover, NLD children were found to be slower in number ordering involving ambiguous positional sizes (where digits making up the numbers were the same). Finally, the best discriminator of NLD and controls was a VSWM task, namely, the sequential lightbulbs recognition task, rather than an arithmetic task, lending support to the hypothesis that VSWM failures are primary with respect to calculation failures, a view also reinforced by the ANCOVA findings.

Appendix

Items of the *Shortened Visuospatial (SVS) Questionnaire* used to obtain the visuospatial score. Teachers are asked to evaluate whether a child presents a given characteristic on a 4-point scale:

- Can the child use tools, such as scissors, set square, or ruler, that require independent and coordinated use of both hands?
- Is the child able to make use of the available space when drawing?
- Does the child understand spoken commands or texts that involve spatial relationships?
- Is the child able to execute complex everyday movements, such as tying shoelaces?
- Does the child show good understanding of spatial relationships in calculation, and can he or she write numbers in columns correctly?
- Does the child have good spatial orientation abilities?
- Is the child good at drawing?
- Is the child competent in learning contexts that rely on visuospatial skills?
- Is the child a good observer of the environment in which he or she lives?
- Does the child demonstrate an interest in new objects, and can he or she deal with them?

Materials for Second- and Third-Grade Children

Written Calculation

4 × 18	15 × 4
32 × 10	157 + 105
6 + 52	55 + 12
58 + 34	35 × 3
47 + 827	23 × 3
8 + 199	8 + 35
13 × 2	13 × 2
42 × 2	790 × 3
29 + 13	24 + 483

Number Ordering From Smallest to Largest

23	15	32	51
76	67	52	25
96	54	69	45

Number Ordering From Largest to Smallest

31	85	58	13
87	24	78	42
53	83	38	35

(continued)

Appendix (continued)

Materials for Fourth- and Fifth-Grade Children

Written Calculation

1574 + 712	512 + 1072
3289 × 403	451 × 14
5 × 52953	413 × 62
734 × 32	829 + 113
541 + 1847	839 × 87
98 + 10909	97355 + 7012
15007 × 105	780790 + 1043
7842 × 159	45924 + 4083
189 × 47	1078 + 70287

Number Ordering From Smallest to Largest

1223	1232	1322	2321
169	691	196	961
2054	2045	2450	2405

Number Ordering From Largest to Smallest

1324	1234	1423	1234
253	523	352	235
2064	2046	4062	6204

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Note

1. The interactions between visuospatial working memory tests and groups were never significant, demonstrating that the slopes of the covariates are homogeneous in the two groups. Specifically, considering number ordering times: sequential light-bulb recognition task by group, $F(1, 38) = .28$, $p = .60$; sequential dot matrix task by group, $F(1, 38) = .22$, $p = .64$; simultaneous dot matrix task by group, $F(1, 38) = 3.09$, $p = .09$. Considering calculation errors: sequential lightbulbs recognition task by group, $F(1, 38) = .35$, $p = .56$; sequential dot matrix task by group, $F(1, 38) = .40$, $p = .53$; simultaneous dot matrix task by group, $F(1, 38) = .25$, $p = .62$.

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