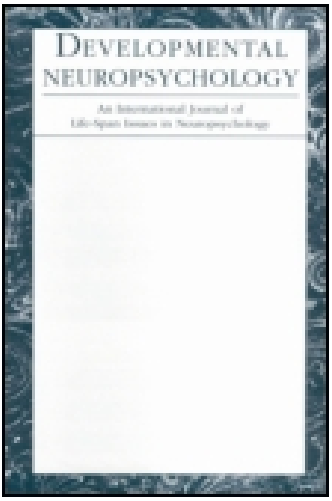

Developmental Neuropsychology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/hdvn20

The Differential Role of Verbal and Spatial Working Memory in the Neural Basis of Arithmetic

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Published online: 21 Aug 2014.

To cite this article: Özlem Ece Demir, Jérôme Prado & James R. Booth (2014) The Differential Role of Verbal and Spatial Working Memory in the Neural Basis of Arithmetic, Developmental Neuropsychology, 39:6, 440-458, DOI: 10.1080/87565641.2014.939182

To link to this article: http://dx.doi.org/10.1080/87565641.2014.939182

DEVELOPMENTAL NEUROPSYCHOLOGY, *39*(6), 440–458

ISSN: 8756-5641 print / 1532-6942 online
DOI: 10.1080/87565641.2014.939182

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We examine the relations of verbal and spatial working memory (WM) ability to the neural bases of arithmetic in school-age children. We independently localize brain regions subserving verbal versus spatial representations. For multiplication, higher verbal WM ability is associated with greater recruitment of the left temporal cortex, identified by the verbal localizer. For multiplication and subtraction, higher spatial WM ability is associated with greater recruitment of right parietal cortex, identified by the spatial localizer. Depending on their WM ability, children engage different neural systems that manipulate different representations to solve arithmetic problems.

An increasing number of functional neuroimaging studies on elementary arithmetic reveal a wide fronto-temporo-parietal network in adults and children. However, our knowledge about individual differences in the neural bases of children's elementary arithmetic skill is limited. Here we asked how the neural bases of multiplication and subtraction vary as a function of working memory (WM) ability in school-age children. This question is of particular significance because large individual differences exist in children's arithmetic skill starting from the early grades (National Center for Education Statistics, 2011). These differences predict later academic achievement more strongly than early reading or socio-emotional skills (Duncan et al., 2007).

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A better understanding of the neural basis of these differences might have implications for early identification and remediation of mathematical difficulties.

The wide fronto-temporo-parietal network underlying elementary arithmetic in adults and children varies depending on the specific operation at hand. Engagement of different neural networks for different operations likely reflects the nature of the representations used to carry out these operations (Dehaene, Piazza, Pinel, & Cohen, 2003; Lee & Kang, 2002). Multiplication problems appear to be solved using verbal representations and rely upon brain regions that underlie verbal representations, such as left lateral temporal cortex, inferior frontal cortex and inferior parietal lobule (Andres, Pelgrims, Michaux, Olivier, & Pesenti, 2011; Dehaene et al., 2003; Lee, 2000; Prado et al., 2011). Subtraction problems, on the other hand, might be solved using spatial-numerical representations and activate brain regions that underlie spatial representations, such as right intra-parietal sulcus and posterior superior parietal cortex (Chochon, Cohen, van de Moortele, & Dehaene, 1999; Lee, 2000; Prado et al., 2011). A small but increasing number of recent studies reveal similar operation specific differences in children, which appear to increase with age (De Smedt, Holloway, & Ansari, 2011; Prado, Mutreja, & Booth, 2014). For example, Prado and colleagues found age-related increases of activity in right parietal cortex for subtraction, but not for multiplication. Conversely, the authors found increases of activity in left temporal cortex for multiplication, but not for subtraction (Prado et al., 2014).

WORKING MEMORY ABILITY AND THE NEURAL BASIS OF ARITHMETIC

The main aim of the current study is to examine whether and how the neural bases of single-digit multiplication and subtraction problems vary as function of WM ability in school-aged children. A growing body of literature suggests that the neural bases of arithmetic in adults and children might vary as a function of individual differences in domain-specific, math-related factors, such as use of retrieval versus calculation strategies (Rosenberg-Lee, Lovett, & Anderson, 2009; Zago et al., 2001) or mathematical proficiency (De Smedt et al., 2011). Here we focus on a domain-general ability that plays an important role in children's arithmetic skill: WM ability. WM refers to the mental workspace that maintains and manipulates information relevant to the cognitive task at hand (Baddeley, 1992). Arithmetic problem solving requires WM resources because it involves holding onto partial information, while processing other information to reach the solution. A behavioral relation between elementary arithmetic and WM is well established in both typically developing children and children with math difficulties (Fuchs et al., 2010; Geary, 2011; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Raghubar, Barnes, & Hecht, 2010).

Existing neuroimaging studies of WM in children and adults also suggest a possible overlap between neural bases of WM and arithmetic. The brain regions involved in arithmetic are also recruited in WM tasks. For example, the right superior parietal cortex is activated in spatial working memory tasks (Geier, Garver, Terwilliger, & Luna, 2008; Smith & Jonides, 1997; Thomason et al., 2009), whereas the left temporo-frontal cortex is engaged during verbal working memory tasks (Smith & Jonides, 1997; Thomason et al., 2009). Moreover, some recent neuroimaging studies in children similarly showed broad relations between WM ability and arithmetic in aforementioned areas (Dumontheil & Klingberg, 2011; Rotzer et al., 2009).

SPECIFIC RELATIONS BETWEEN VERBAL AND SPATIAL WORKING MEMORY AND NEURAL BASIS OF ARITHMETIC

Although a broad relation between WM ability and arithmetic skill is well established, the specific nature of this relation remains underspecified. Working memory is not a unitary construct and has multiple components; including verbal and spatial WM. Verbal WM ability is argued to play a role in formation of and access to high-quality verbal representations (Berch, 2008; Unsworth & Engle, 2007). Spatial WM enables formation of and access to high quality spatial representations (Berch, 2008; Raghubar et al., 2010; Unsworth & Engle, 2007).

Empirical evidence on the specific relations between WM ability and arithmetic is scarce. Several studies only examine the role of verbal WM ability in arithmetic skill. Most studies do not examine different arithmetic operations when examining the relations to verbal and spatial WM ability (Ashkenazi, Rosenberg-Lee, Metcalfe, Swigart, & Menon, 2013; Metcalfe, Ashkenazi, Rosenberg-Lee, & Menon, 2013; Meyer et al., 2010). Moreover, theoretical predictions are mixed. In line with the neuroimaging results discussed above, some behavioral studies suggest that multiplication more strongly relates to verbal WM than spatial WM. Conversely, subtraction is argued to more strongly relate to spatial WM than verbal WM (Lee & Kang, 2002). However, other studies/theories predict better subtraction performance to be associated with higher verbal working memory, suggesting that subtraction relies on verbal representations of numbers in intermediate stages of subtraction process (Hecht, 2002). A third prediction is based on neuroimaging studies showing that multiplication might rely both on verbal and spatial representations of numbers (Ischebeck et al., 2006). According to this view, better multiplication performance should be associated with higher verbal and spatial WM.

No neuroimaging study has examined the reliance of these different operations on WM and this relation has not been tested in children. We argue that the mechanism by which WM ability relates to arithmetic performance is through the quality of verbal and spatial representations. Children with higher verbal or spatial WM ability are able to form and access higher quality verbal or spatial representations (Berch, 2008; Raghubar et al., 2010; Unsworth & Engle, 2007). These higher quality representations are in turn relied on during multiplication and subtraction. In the current study, using functional magnetic resonance imaging (fMRI), we independently identified regions supporting verbal and spatial representations using localizer tasks, which constituted our regions of interest (ROIs). We used a word rhyming task to localize brain regions that subserve verbal representations. Previous literature showed that this word rhyming task taps onto phonological representations and successfully localizes regions involved in verbal representations in left temporo-parietal and inferior frontal cortices (Booth, 2010; Prado et al., 2011, 2014). We used a dot comparison task to localize brain regions that subserve spatial representations. Previous literature showed this dot comparison task taps into spatio-numerical representations and successfully localizes regions involved in spatial representations in right intraparietal sulcus and superior parietal lobule (Prado et al., 2011, 2014). Importantly, performance on tasks similar to these have been shown to relate to mathematical skill (Halberda, Mazzocco, & Feigenson, 2008; Hecht, Torgesen, Wagner, & Rashotte, 2001; Krajewski & Schneider, 2009; Piazza et al., 2010).

Brain activity of 9- to 12-year-old children was measured while they evaluated single-digit subtraction and multiplication problems of varying problem sizes (i.e., small versus large problems). Behavioral standardized measures of verbal and spatial WM ability were also administered before scanning. These three pieces of information (i.e., independent localizer tasks, arithmetic tasks and WM measures) enabled us to triangulate how verbal and spatial WM ability relates to reliance on brain regions that subserve verbal and spatial representations during multiplication and subtraction. On the basis of the previous literature, we expected that verbal WM ability would specifically relate to brain activation subserving verbal representations during multiplication, whereas spatial WM ability would specifically relate to brain activation subserving spatial representations during subtraction. To our knowledge, our study is the first to examine whether and how the neural bases of multiplication and subtraction vary as function of verbal and spatial WM ability, and what the behavioral performance implications of these relations are in school-age children.

MATERIALS AND METHODS

Participants

Forty-eight children were recruited from schools in the greater Chicago area to participate in the study. All children (1) were native English speakers, (2) were free of past or present neurological or psychiatric disorders, (3) had no history of reading, oral language, intelligence, or attention deficits, (4) scored higher than 80 standard score on full-scale IQ as measured by Wechsler Abbreviated Scale of Intelligence (WASI; Weschler, 1999), and (5) scored higher than 90 standard score on arithmetic as measured by the Comprehensive Mathematical Abilities Test (CMAT; Hresko, Schlieve, Herron, Swain, & Sherbenou, 2003). Data from eight participants were excluded because of excessive movement in the scanner (see criteria below), poor whole-brain coverage (i.e., insufficient coverage of the superior parietal or inferior temporal lobe), low behavioral accuracy in the scanner (i.e., lower than 40% in the arithmetic tasks) or response bias in the scanner (i.e., false alarm to misses ratio greater than 2 and false alarm rate greater than 50%). The remaining 40 participants from 9 to 12 years of age were included in the analyses (23 females, mean age = 10.9, standard deviation = 1.4, range = 9 to 12.9). Written consent was obtained from the children and their parents/guardians. All experimental procedures were approved by the Institutional Review Board at Northwestern University.

Standardized Measures

Children were administered standardized measures to assess their intellectual, reading, mathematical, and working memory abilities. IQ was measured by the Verbal (Vocabulary, Similarities) and Performance (Block Design, Matrix Reasoning) subtests of the WASI (Weschler, 1999). Reading skill was assessed by Letter-Word Identification subtest of the Woodcock-Johnson III Tests of Achievement (WJ-III) (Woodcock, McGrew, & Mather, 2001). The Letter-Word Identification subtest requires children to name letters and read words aloud from a list. Mathematical ability was assessed with the Basic Calculations subtest of the CMAT (Hresko et al., 2003). The Basic Calculations subtest requires children to solve increasingly more difficult addition, subtraction, multiplication, and division problems.

TABLE 1
Performance on Standardized Tests

	Average (SD)	*Range*
WASI Full Scale IQ	116 (14)	86–144
WJ		
Letter-Word Identification	111 (10)	93–133
CMAT		
Basic Calculation	119 (18)	93–130
AWMA		
Verbal Working Memory	107 (15)	78–142
Spatial Working Memory	114 (14)	87–143

Working memory ability was measured by the Spatial Recall and the Listening Recall subtests of the Automated Working Memory Assessment (AWMA) (Alloway, Gathercole, & Pickering, 2007). Both subtests have a dual nature in that both involve simultaneous storage and processing of spatial or verbal information. The Spatial Recall subtest requires children to view pairs of shapes, where the shape on the right has a red dot near it. The shape on the right is either the same shape as on the left when rotated in two dimensions or its mirror image. After viewing each pair, children are asked to determine whether the shape on the right is the same when rotated or the mirror image of the shape on the left. They are also told to remember the position of the red dot. The number of pairs per item increases as children proceed through the subtest. At the end of each item, children are asked to recall the correct position of the red dot in correct temporal order. Thus, children are asked to store the location of the red dot, as they process new shapes and decide if the pair of shapes is the same or not. The Listening Recall subtest requires children to decide whether a sentence is true or false and also to remember the final word of the sentence. Thus, children are asked to store the final word of the sentence, as they process new sentences and decide whether they are true or false. The number of sentences per item increases as children proceed through the subtest. The item is scored as correct if children recall the correct word or words in the correct temporal order. Table 1 summarizes children's performance on standardized tests based on the published age norms.

Arithmetic Tasks

In each trial of the multiplication task, children were asked to evaluate whether the answer to a single-digit multiplication problem was true or false. Twenty-four number pairs were used, covering the full range of single-digit multiplication problems (with the exceptions below). 12 "small" and 12 "large" problems were included in the task. Operands of small problems were smaller than or equal to 5 (e.g., 3×4). Operands of large problems were larger than 5 (e.g., 6×7). Each pair was repeated twice with a true answer (e.g., $3 \times 4 = 12$) and once with a false answer. Thus, children were presented with 72 problems in total. False answers were created by replacing the correct answer by an answer that would have been obtained by adding or subtracting 1 from the first operand (e.g., $3 \times 4 = 16$). Problems with 0 as an operand (e.g., 3 × 0), problems with 1 as an operand (e.g., 3 × 1), and tie problems where the first and second operand are identical (e.g., 3 × 3) were not used in the main experiment, but were used in the practice sessions to familiarize the children to the task. Twenty-four problems were used in the practice sessions.

In each trial of the subtraction task, children were asked to evaluate whether the answer to a single-digit subtraction problem was true or false. Twenty-four number pairs were used, covering the full range of single-digit subtraction problems (with the exceptions below). Twelve "small" and 12 "large" problems were included in the task. In small problems, the difference between the first and second operand was small (i.e., 1, 2, or 3). In large problems, the difference between the first and second operand was large (i.e., 4, 5, or 6), and a large first term was used (i.e., 6, 7, 8, or 9). Each pair was repeated twice with a true answer (e.g., 5 – 3 = 2) and once with a false answer. Thus, children were presented with 72 problems in total. False answers were created by subtracting 1 from the correct answer (e.g., 5 – 3 = 1) or by adding 1 or 2 to the correct answer (e.g., 5 – 3 = 4). Problems with 0 or 1 as the second operand (e.g., 5 – 0), tie problems where the first and second operand are identical (e.g., 5 – 5) and problems where the correct answer corresponded to the second term (e.g., 6 – 3) were not used in the main experiment, but were used in the practice sessions to familiarize the children to the task. Twenty-four problems were used in the practice sessions. Problems where the first operand is smaller than the second (e.g., 3 – 5) were not used in the main experiment or the practice session.

Localizer Tasks

In each trial of the verbal localizer, two words were sequentially presented. Children were asked to evaluate whether the two words rhymed or not. All words were monosyllabic English words with varying orthographic and phonological similarity (e.g., dime – lime, pint – mint, jazz – has, press – list). Similarity was manipulated so that responses could not be based on spelling alone. Forty-eight word pairs were used in the main experiment and 48 word pairs were used in the practice session. In each trial of the spatial localizer, two dot arrays were sequentially presented. Children were asked to decide which of the two dot arrays were composed of a larger number of dots. Arrays of 12, 24, and 36 dots were used with varying single dot sizes and cumulative surface area. Seventy-two pairs of dot arrays were used in the main experiment and 36 pairs were used in the practice session. Average accuracy on the verbal localizer task was 83% (*SD* = 12) and average RT was 1,153 msec (*SD* = 248). Average accuracy on the spatial localizer task was 89% (*SD* = 11) and RT was 977 msec (*SD* = 283).

Experimental Procedure

After informed consent was obtained and standardized tests were administered, children participated in a practice session. During the practice session, children learned to minimize their head movement in a mock fMRI scanner (with feedback from an infrared tracking device). To ensure that children understood all the tasks and were familiarized with the fMRI environment, they practiced all four tasks in the mock fMRI scanner. The actual fMRI scanning session took place within one week of the practice session. In the fMRI scanner, multiplication, subtraction and spatial localizer tasks were divided into 2 runs of about 4 minute each. The verbal localizer task was administered in a single run lasting about 7 minutes. The order of tasks was counterbalanced across participants. Behavioral responses were recorded using an MR-compatible keypad placed below the right hand. Visual stimuli were generated using E-prime software (Schneider, Eschman, & Zuccolotto, 2002), and projected onto a translucent screen. Children viewed the screen through a mirror attached to the head coil.

Stimulus timing was identical in all tasks. A trial started with the presentation of a first stimulus (subtraction, multiplication, dot array or word depending on the task) for 800 msec, followed by a blank screen for 200 msec. A second stimulus (subtraction, multiplication, dot array, or word depending on the task) was presented for 800 msec, followed by a red fixation square presented for 200 msec. Participants were asked to make a response during an interval ranging from 2,800 msec to 3,600 msec. Twenty-four null trials were included in the multiplication, subtraction and spatial localizer tasks. Twelve null trials were used for the verbal localizer task. In the null trials, a blue square was presented for the same duration as the experimental conditions and children were asked to press a button when the square turned red. The timing and order of trial presentation within each run was optimized for estimation efficiency using Optseq2 (http://surfer.nmr.mgh.harvard.edu/optseq/).

fMRI Data Acquisition

Images were collected using a Siemens 3T TIM Trio MRI scanner (Siemens Healthcare, Erlangen, Germany) at Northwestern University's Center for Translational Imaging (CTI). The fMRI blood oxygenation level-dependent (BOLD) signal was measured with a susceptibility weighted single-shot echo planar imaging (EPI) sequence. The following parameters were used: TE = 20 msec, flip angle = 80°, matrix size = 128 × 120, field of view = 220 × 206.25 mm, slice thickness = 3 mm (0.48 mm gap), number of slices = 32, TR = 2,000 msec. Before functional image acquisition, a high resolution T1-weighted 3D structural image was acquired for each subject (TR = 1,570 msec, TE = 3.36 msec, matrix size = 256 × 256, field of view = 240 mm, slice thickness = 1 mm, number of slices = 160).

fMRI Data Analyses

Data analyses were performed using SPM8 (Statistical Parametric Mapping) (http://www.fil.ion.ucl.ac.uk/spm). The first six images of each run were discarded, functional images were corrected for slice acquisition delays, realigned to the first image of the first run to correct for head movements, and spatially smoothed with a Gaussian filter equal to about twice the voxel size (4 × 4 × 8 mm^3 full width at half maximum). ArtRepair software was used to suppress residual fluctuations due to large head motion and to identify volumes with significant artifact and outliers relative to the global mean signal (4% from the global mean). Volumes showing rapid scan-to-scan movements of greater than 1.5 mm were excluded via interpolation of the two nearest nonrepaired volumes. All participants had less than 5% of the total number of volumes replaced in a single run. Interpolated volumes were partially deweighted when first-level models were calculated on the repaired images (Mazaika, Hoeft, Glover, & Reiss, 2009). Functional volumes were co-registered with the segmented anatomical image and normalized to the standard T1 Montreal Neurological Institute (MNI) template volume (normalized voxel size, 2 × 2 × 4 mm^3).

1st-level analyses. Event-related statistical analyses were performed according to the General Linear Model. Activation was modeled as epochs with onsets time-locked to the presentation of the first stimulus and with a duration matched to the length of the trial (2 seconds). For the arithmetic tasks, all responses were included in the model, but only responses in problems with a true answer were considered of interest in the analyses. All epochs were convolved with a canonical hemodynamic response function. The time series data were high-pass filtered (1/128 Hz), and serial correlations were corrected using an autoregressive AR(1) model. Effect sizes were estimated using linear statistical contrasts and subsequently entered into 2nd-level analyses.

2nd-level analyses. In order to evaluate the relations between behavioral scores on WM and neural bases of arithmetic, 2nd-level voxel-wise regression models were created. Voxel-wise regression analyses were conducted to identify the brain regions that showed an increase or a decrease in activity during the evaluation of small or large arithmetic problems (multiplication or subtraction) with respect to WM scores (verbal WM or spatial WM) across subjects. The analyses were conducted separately for each arithmetic operation and problem size. In each analysis, verbal and spatial WM ability constituted the regressors of interest. Additionally, we included two regressors of no interest. These encoded accuracy on the type of arithmetic problem, as well as the interactions between accuracy on the arithmetic problem and the relevant WM score. All analyses were repeated with RT as our measure of performance on arithmetic task instead of accuracy, but the results remain unchanged. Moreover, removing the interaction term did not change the pattern of results.

Our goal was to identify the brain regions in which differences of activity between subjects can be explained by differences in verbal versus spatial WM scores (and vice versa). Therefore, we identified the regions in which brain activity was more strongly associated with verbal WM than spatial WM (and vice versa) by directly contrasting the two regressors of interest in each analysis (see above). This enabled us to identify the regions in which differences of activity between-subjects were more strongly associated with differences in verbal than spatial WM (contrast [1 –1]), as well as more strongly associated with differences in spatial than verbal WM (contrast [–1 1]).

ROI definition. Verbal and spatial ROIs were identified using the localizer tasks. Verbal ROIs were identified using the verbal localizer contrast (contrast of [words versus null trials] minus [dots versus null trials] across all subjects). Spatial ROIs were identified using the spatial localizer contrast (contrast of [dots versus null trials] minus [words versus null trials]). Because of our specific *a priori* hypotheses concerning the role of regions involved in verbal and spatial representations, we constrained our analyses with anatomical masks (using the aal atlas). Based on previous literature, an anatomical mask consisting of the inferior frontal gyrus (IFG), superior temporal gyrus (STG), and middle temporal gyrus (MTG) of the left hemisphere was used to constrain activations associated with the verbal localizer contrast (Booth, 2010). An anatomical mask consisting of the inferior parietal lobule (IPL) and superior parietal lobule (SPL) (which included the intraparietal sulcus, IPS) of the right hemisphere was used to constrain activations associated with the spatial localizer contrast (Prado et al., 2011). The resulting masks were thresholded using voxel-wise significance levels set at $p < .05$ and cluster extent of 20 contiguous voxels.

The verbal localizer contrast was associated with activity in the left MTG and STG, as well as in the left IFG (see Figure 1A). The peak coordinates of left IFG and MTG were close to coordinates identified in a previous studies using the same rhyming task (Euclidian distance of 14 mm for left IFG, 18 mm for left MTG) (Prado et al., 2011, 2014). These clusters constituted the verbal localizer mask. The spatial localizer contrast was associated with activity in one cluster spanning right SPL and IPL, which included the right IPS (see Figure 2A). The peak coordinate of the cluster was close to coordinates identified in previous studies using the same numerosity

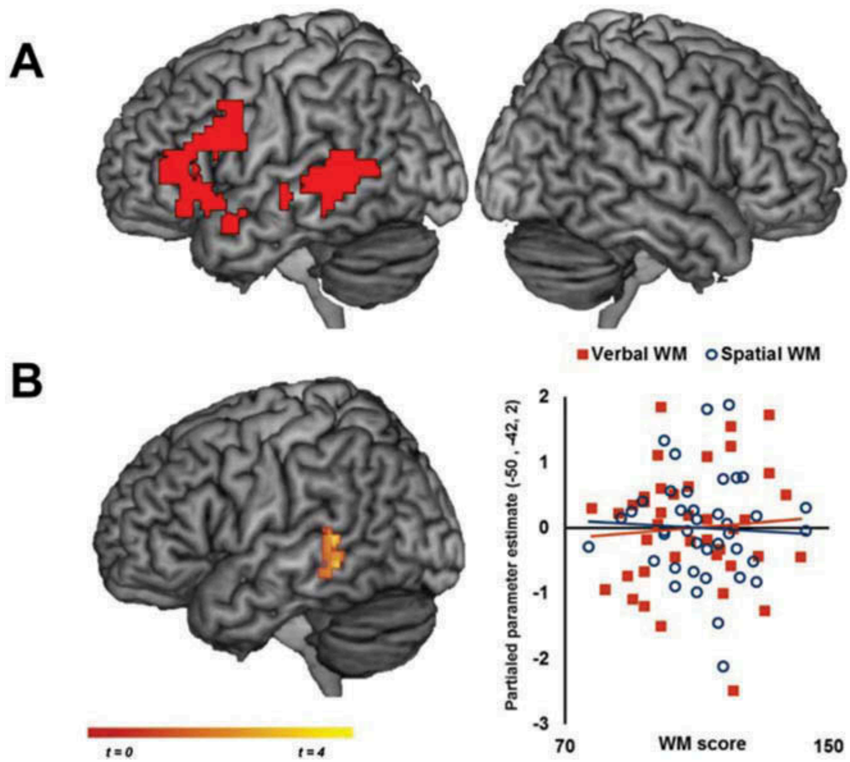

FIGURE 1 Relation of working memory (WM) to verbal mechanisms underlying arithmetic. (A) The verbal localizer task was associated with enhanced activity in a network that included left middle (peak coordinate: x = –64, y = –46, z = 6, BA = 21/22, z = 4.09, size = 398 voxels), middle/superior temporal (peak coordinate: x = –42, y = 6, z = –22, BA = 21/38, z = 3.46, size = 61 voxels), and inferior frontal gyrus (peak coordinate: x = –52, y = 8, z = 2, BA = 9/45/46, z = 3.95, size = 467 voxels). (B) Activity in the verbal region of interest (ROI) that shows a stronger correlation with verbal WM than spatial WM for large multiplication problems. Average brain activity for large problems was extracted from the significant cluster in left middle temporal gyrus (MTG), partialed out for variables of no interest, and plotted against verbal and spatial WM scores for visualization purposes only.

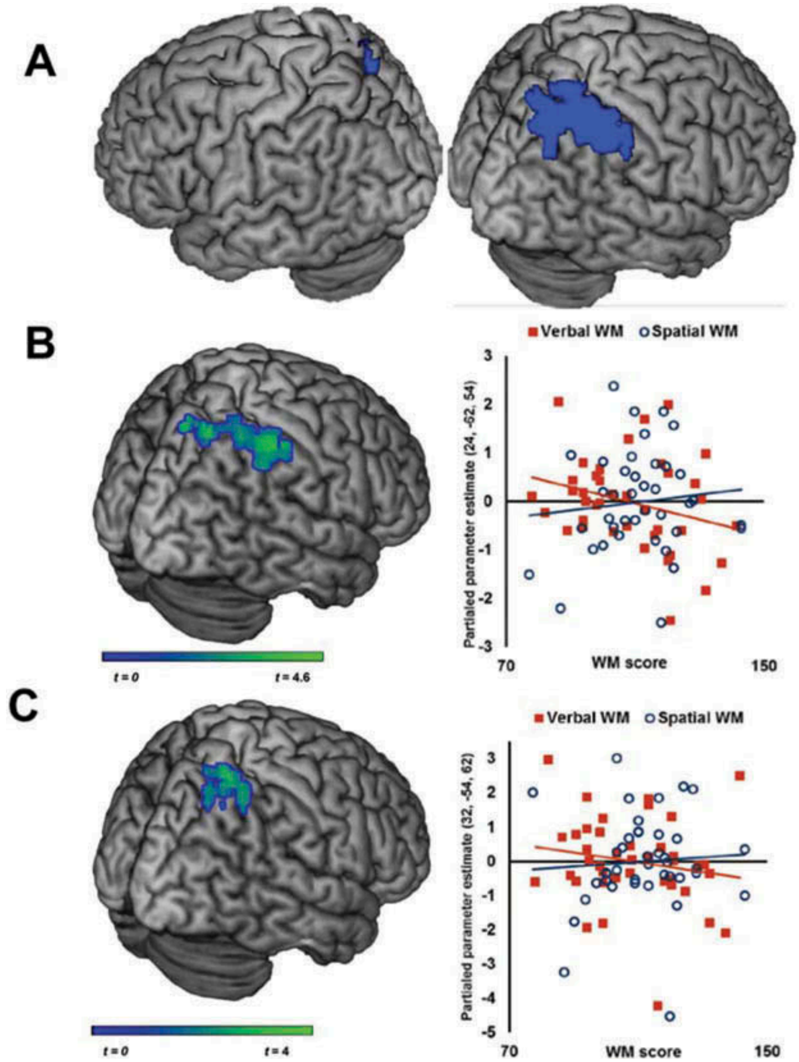

FIGURE 2 Relation of working memory (WM) to spatial mechanisms underlying arithmetic. (A) The spatial localizer task was associated with enhanced activity in a network that included right inferior and superior parietal lobule (peak coordinate: x = 22, y = –64, z = 54, BA = 7/40, z = 5.38, size = 712 voxels). (B) Activity in the spatial regions of interest (ROI) that shows a stronger correlation with spatial WM than verbal WM for large multiplication problems. Average brain activity for large problems was extracted from the significant cluster in the right intraparietal sulcus (IPS), partialed out for variables of no interest, and plotted against verbal and spatial WM scores for visualization purposes only. (C) Activity in the spatial ROI that shows a stronger correlation with spatial WM than verbal WM for large subtraction problems. Average brain activity for large problems was extracted from the significant cluster in right IPS, partialed out for variables of no interest, and plotted against verbal and spatial WM scores for visualization purposes only.

task (Euclidian distance of 18 mm for right IPS) (Prado et al., 2014). These clusters constituted the spatial localizer mask.

ROI analyses. Statistical significance within each of these masks was defined using Monte Carlo simulations (using AFNI's AlphaSim program; http://afni.nimh.nih.gov/). For subsequent analyses, in order to reach corrected level threshold (alpha = 0.05) within the verbal ROIs for a height threshold of $p < .05$, the cluster needed to be 48 voxels. For the spatial ROIs, for a height threshold of $p < .05$, the cluster needed to be 67 voxels. Relations of arithmetic to WM were examined in the ROIs.

Whole brain analysis. Statistical significance for the whole brain analysis was defined using Monte Carlo simulations (using AFNI's AlphaSim program; http://afni.nimh.nih.gov/). In order to reach corrected level threshold (alpha = 0.05) at the whole brain level for a height threshold of $p < .05$, the cluster needed to be 765 voxels.

RESULTS

Task Performance

Table 2 summarizes children's performance on the multiplication and subtraction tasks. We ran three ANOVAs on accuracy and reaction time (RT) with problem size (small, large) and operation (multiplication, subtraction) as within-subjects independent variables. The ANOVA on accuracy revealed a main effect of problem size $F(1, 39) = 40.01$, $p < .01$, such that children answered a lower portion of the large problems correctly as compared to small problems. Children's accuracy did not vary as a function of operation $F(1, 39) = 2.65$, $p = .11$. The interaction between operation and problem size was significant, $F(1, 39) = 30.76$, $p < .01$, such that the problem size effect was larger for multiplication than subtraction. The ANOVA on RT similarly revealed a main effect of problem size, $F(1, 39) = 53.27$, $p < .01$, where RTs were longer on large problems than small problems. The main effect of operation was not significant, $F(1,39) = 1.88$, $p = .18$. The interaction term between operation and problem size was significant $F(1, 39) = 11.27$, $p < .01$, such that the problem size effect was larger for multiplication than subtraction. Overall, these

TABLE 2
Performance on Experimental Tasks

	Accuracy (SD)	*RT (SD)*
Multiplication		
Small	0.95 (0.08)	889 (311)
Large	0.77 (0.18)	1143 (383)
Subtraction		
Small	0.91 (0.11)	1004 (305)
Large	0.87 (0.15)	1137 (340)

results showed that problem size manipulation was effective, although the effect was larger for multiplication problems.

Verbal and spatial WM scores were significantly correlated with each other, $r = 0.40$, $p < .05$. However, note that all of our fMRI analyses included both verbal and spatial WM scores as regressors of interest, such that these variables were never confounded. Accuracy on small ($r = 0.32$, $p < .05$), but not large multiplication problems ($r = 0.24$, $p = .14$), was correlated with verbal WM scores. Accuracy on both small ($r = 0.37$, $p < .05$), and large subtraction problems ($r = 0.43$, $p < .05$) was correlated with spatial WM scores. Accuracy on subtraction problems was not correlated with verbal WM scores and accuracy on multiplication problems was not correlated with spatial WM scores (all p's $> .05$). Because of the significant correlations with accuracy on the task, accuracy on the arithmetic problem of interest and the interaction between accuracy and the WM score of interest were partialed out in the fMRI regression analyses. Because accuracy and RT revealed similar pattern of results, only accuracy as a control for arithmetic performance in fMRI analyses is reported (see Methods). Age was not correlated to verbal ($r = 0.08$, $p = .62$) or spatial WM ($r = 0.15$, $p = .36$) scores.

Activation During Multiplication and Subtraction Tasks

Multiplication problems significantly activated a cluster in left MTG (peak coordinate: x = −50, y = 4, z = 38, BA = 21, $z = 4.05$, size = 168 voxels), and a cluster in left IFG (peak coordinate: x = –64, y = –34, z = 2, BA = 22, $z = 3.79$, size = 183 voxels) more than the baseline. Multiplication problems also activated a marginally significant cluster in the right IPS, (peak coordinate: x = 34, y = –60, z = 46, BA = 7, $z = 4.21$, size = 54 voxels). Subtraction problems significantly activated a cluster in right IPS (peak coordinate: x = 44, y = –42, z = 46, BA = 7, $z = 3.44$, size = 367 voxels). Subtraction problems also activated three clusters, two in left MTG (peak coordinate: x = –46, y = –44, z = 6, BA = 21, $z = 3.23$, size = 135 voxels, peak coordinate: x = –66, y = –36, z = 6, BA = 21, $z = 2.65$, size = 53 voxels) and one in left IFG (peak coordinate: x = –48, y = 6, z = 30, BA = 9, $z = 3.82$, size = 129 voxels).

Relationship Between WM Ability and Activity During the Multiplication Task

Verbal WM. We first examined the relations between verbal WM and the neural basis of small or large multiplication problems using 2nd-level voxel-wise regression analyses (see Methods). We identified the brain regions within our verbal or spatial ROIs where activity during the evaluation of small or large multiplication problems showed a stronger association with verbal WM than with spatial WM (when the effects of variables of no-interest are controlled). For small problems, we found a stronger association between activity and verbal WM than spatial WM in the left MTG, however this activation did not reach significance (peak coordinate: x = –50, y = –42, z = 2, BA = 22, $z = 2.34$, size = 29 voxels). For large problems, we found a significant and stronger association between activity and verbal than spatial WM in an overlapping cluster in left MTG (peak coordinate: x = –50, y = −42, z = 2, BA = 22, $z = 3.87$, size = 54 voxels) (see Figure 1B). For visualization purposes, we extracted the average beta weight from the significant cluster, and plotted it against verbal and spatial WM scores. This plot showed that verbal WM was more positively associated with activity during multiplication than spatial WM (see Figure 1B). To ensure that the differential pattern was due to increases of activity as verbal WM score increased and not to decreases of activity as spatial WM score increased, we examined the simple relation between verbal WM and brain activity. Verbal WM was positively associated with activity in the left MTG during the evaluation of large multiplication (peak coordinate: x = –50, y = –42, z = 2, BA = 22, z = 3.85, size = 61 voxels). There were no significant clusters within the spatial ROIs that were more strongly associated with verbal WM than spatial WM for large problems.

Spatial WM. We then examined the relations between spatial WM and the neural basis of small or large multiplication. We identified brain regions within our verbal or spatial ROIs where activity during the evaluation of small or large multiplication problems showed a stronger association with spatial WM than with verbal WM (when the effects of variables of no-interest are controlled). For small problems, we found a stronger association between activity and spatial than verbal WM in voxels located along the intraparietal sulcus (IPS) (peak coordinate: x = 50, y = –32, z = 50, BA = 40, z = 3.76, size = 357 voxels). For large problems, we also found a stronger association between activity and verbal than spatial WM in voxels located along the IPS (peak coordinate: x = 24, y = –62, z = 54, BA = 7, z = 3.26, size = 180 voxels), slightly more posterior to the peak for small problems (see Figure 2B). For visualization purposes, we extracted the average beta weight from the significant cluster, and plotted it against verbal and spatial WM scores for large problems. This plot showed that spatial WM was more positively associated with activity during large multiplication than verbal WM (see Figure 2B). To ensure that the differential patterns observed for small or large problems were due to increases of activity as spatial WM score increased and not to decreases of activity as verbal WM score increased, we examined the simple relation between spatial WM and brain activity. These analyses confirmed that spatial WM was positively associated with activity along the IPS (peak coordinates for small problems: x = 50, y = –32, z = 50, BA = 40, z = 3.86, size = 364 voxels; peak coordinates for large problems: x = 24, y = –62, z = 54, BA = 7, z = 3.20, size = 153 voxels). We did not find any stronger relationship between activity and spatial than verbal WM in any of the verbal ROIs.

Summary. For large multiplication problems, higher verbal WM was associated with greater recruitment of the left MTG, which underlie verbal representations. For both small and large multiplication problems, higher spatial WM was associated with greater activity along the right IPS, which underlies spatial representations. Importantly the relations were specific as verbal WM was not related to activation in spatial ROIs and spatial WM was not related to activation in verbal ROIs.

Relationship Between WM Ability and Activity During the Subtraction Task

Verbal WM. We examined the relations between verbal WM and the neural basis of small or large subtraction problems. There were no brain regions within our verbal or spatial ROIs where activity during the evaluation of subtraction problems was more associated with verbal WM than with spatial WM.

Spatial WM. We then examined the brain regions within our verbal and spatial ROIs where activity during the evaluation of small or large subtraction problems was differentially associated with spatial WM and verbal WM (when the effects of variables of no-interest are controlled).

For small subtraction problems, we found a stronger association between activity and spatial than verbal WM along the IPS (peak coordinates: x = 20, y = –50, z = 62, BA = 7, z = 3.60, size = 147 voxels). This cluster overlapped with the clusters that showed a positive relationship between spatial WM and both small and large multiplication. For large problems, we also found a stronger association between activity and spatial than verbal WM along the IPS (peak coordinates: x = 32, y = –54, z = 62, BA = 40, z = 2.73, size = 109 voxels). This cluster also overlapped with the clusters that showed a positive relation between spatial WM and both small and large multiplication (see Figure 2C). A plot showed that spatial WM was more positively associated than verbal WM with activity during large subtraction in this region (Figure 2C). To ensure that the differential patterns observed for small and large problems were due to increases of activity as spatial WM score increased and not to decreases of activity as verbal WM score increased, we examined the simple relation between spatial WM and brain activity. These analyses confirmed that spatial WM was positively associated with activity during the evaluation of small and large subtraction in the right IPS (peak coordinate for small subtraction: x = 20, y = –50, z = 62, BA = 7, z = 2.71, size = 139 voxels, peak coordinate for large subtraction: x = 32, y = –54, z = 62, BA = 7, z = 2.48, size = 98 voxels). For both small and large problems, there were no brain regions within our verbal ROIs where activity during the evaluation of large subtraction problems was more associated with spatial WM than verbal WM.

Summary. During small and large subtraction problems, verbal WM was not significantly associated with brain activation in the verbal or spatial ROIs. Spatial WM was associated with greater recruitment of a cluster in IPS, which underlies spatial representations. Importantly the relations were specific as spatial WM was not related to activation in verbal ROIs.

Whole Brain Analysis

Correlations between verbal and spatial WM and activation during multiplication and subtraction problems were confirmed at the whole brain level. Spatial WM was associated with significant activation in a cluster overlapping with right IPS activation reported in the ROI analyses (peak coordinate for small multiplication: x = 50, y = –32, z = 50, BA = 40, peak coordinate for large multiplication: x = 24, y = –62, z = 54, BA = 7, peak coordinate for small subtraction: x = 20, y = –50, z = 62, BA = 7, peak coordinate for large subtraction: x = 32, y = –54, z = 62, BA = 7). Verbal WM and multiplication was reliable at reduced height threshold of $p = 0.1$, in a cluster overlapping with the left MTG activation reported in the ROI analyses (peak coordinate for large multiplication: x = –50, y = –42, z = 2, BA = 22).

DISCUSSION

The goal of the present study was to examine how the neural bases of elementary arithmetic vary as a function of verbal and spatial WM ability. We hypothesized that there would be specific links between different types of WM and the distinct neural bases multiplication and subtraction. The results showed that inter-individual differences in verbal WM (as compared to spatial WM) ability was associated with inter-individual differences in brain activity of brain regions that subserve verbal representations (i.e., left MTG) during large multiplication problems. This was not observed for subtraction problems. We also found that inter-individual differences in spatial WM ability (as compared to verbal WM) was associated with inter-individual differences in brain activity of brain regions that subserve spatial representations (i.e. right IPS) during both multiplication and subtraction problems. We discuss each of these findings and their implication in turn.

Working Memory Ability and Neural Basis of Multiplication

As compared to spatial WM, higher verbal WM was associated with increased activity in left MTG during multiplication problems. Left temporo-parietal cortices are widely thought to support verbal representations, such as representations of the associations between words (Booth, 2010; Fiebach, Friederici, Müller, & von Cramon, 2002). Operations such as multiplication are considered to rely on similar verbal representations. This is because in learning to solve these problems, children are taught to memorize associations between multiplication problems and their solutions (Dehaene et al., 2003). In keeping with this idea, the left MTG is activated for multiplication in adults (Andres et al., 2011; Prado et al., 2011), shows increased activation with age and with training (Ischebeck, Zamarian, Egger, Schocke, & Delazer, 2007; Prado et al., 2014), and reduced activation in children with math difficulties (Ashkenazi, Rosenberg-Lee, Tenison, & Menon, 2012). Our results build on the existing literature by showing that the extent to which children rely on verbal representations in left MTG during multiplication varies as a function of inter-individual differences in verbal WM ability. Children with higher verbal WM ability might have formed stronger associations between multiplication problems and their solutions when learning these problems. Thus, the relation between higher verbal WM and increased activation in left MTG can be interpreted to reflect strength of associations between multiplication problems and their solutions that are represented in left MTG. The relation of verbal WM to activation in left MTG was significant for large problems, but marginal for small problems. Children are less frequently exposed to large problems and are exposed to them later than small problems (Campbell & Xue, 2001; LeFevre, Sadesky, & Bisanz, 1996). Stronger verbal WM ability might have been played a particularly important role for forming verbal associations when learning such infrequent problems. Supporting this view, left MTG (as well as left angular gyrus) has been shown to be activated during the acquisition of new multiplication facts in adults (Ischebeck et al., 2007).

Although not anticipated, we also found that the neural basis of multiplication varies as a function of spatial WM ability. Higher spatial WM, as compared to verbal WM, was associated with increased activity in right IPS during multiplication. Previous literature on multiplication shows that young children rely on spatial representations of numerical quantities, and mastering multiplication might involve a shift to reliance on verbal representations with practice (Ashcraft, 1983; Lemaire & Siegler, 1995). Although both behavioral and neuroimaging studies suggest that multiplication tends to increasingly rely on verbal representations with age, our results suggest that children continue to use multiple routes for multiplication (Delazer et al., 2005; LeFevre, Bisanz, et al., 1996). The right IPS has been shown to underlie spatial representations and is generally activated in spatial WM tasks (Cavanna & Trimble, 2006; Smith & Jonides, 1997). Children with higher spatial WM ability might have built better quality spatial representations for numerical quantities, possibly on a mental number line, and might effectively use these spatial representations for solving multiplication problems (Ashkenazi et al., 2013; Rotzer et al., 2009). Indeed, activation in right IPS is observed when adults are first learning to solve novel multiplication problems or when adults report using spatial representations of numerical quantities to solve multiplication problems (Delazer et al., 2003; Ischebeck et al., 2007). Thus, performance on multiplication problems at any age is a mixture of multiple approaches, including not only retrieval of verbal representations, but also manipulation of spatial representations of numbers. The specific approach taken depends on the effectiveness of the approach for the problem solver—which as we show might depend on their WM ability (Lemaire & Siegler, 1995).

Working Memory Ability and Neural Basis of Subtraction

Unlike for multiplication, we did not find a relation between verbal WM and brain activity during subtraction. However, our results indicate a relation between spatial WM and brain activity during subtraction. Specifically, higher spatial WM (as compared to verbal WM ability) was associated with increased activity in right IPS during subtraction problems. The right IPS is activated in adults during subtraction, exhibits increased activation with age and training, and shows reduced activation in children with math difficulties (Ashkenazi et al., 2012; De Smedt et al., 2011; Kaufmann, Wood, Rubenstein, & Henik, 2011; Lee, 2000; Lemer, Dehaene, Spelke, & Cohen, 2003; Prado et al., 2014). Our findings are in line with the previous literature suggesting that children and adults primarily rely on spatial, not verbal, representations in solving subtraction problems. Indeed, behavioral studies that employ dual-task paradigms and show that verbal suppression does not interfere with performance on subtraction problems in adults (Lee & Kang, 2002). Similarly, recent fMRI training studies show that even after repeated training in solving subtraction problems, adults do not transition to relying on areas that subserve verbal representations, but continue to rely on areas that subserve spatial representations, such as the right IPS (Ischebeck et al., 2006). Specifically, the representations hosted in right IPS have been described to be preverbal and abstract in nature (Dehaene et al., 2003). We extend this literature showing that the neural basis of subtraction does not vary as a function of verbal WM ability. Instead, we show that the degree to which children rely on spatial representations in right IPS varies depending on their spatial WM ability. This might be because, in learning to solve subtraction problems, children are taught to manipulate numerical quantities (Dehaene et al., 2003). Children with higher spatial WM ability might have formed stronger spatial representations of numerical quantities. Thus, the relation between higher spatial WM and increased activation in right IPS might reflect the strength of these representations when solving subtraction problems.

Implications

To our knowledge, the current study is the first to show the specific relations between neural underpinnings of multiplication and subtraction and a domain-general ability in children. Although the main theories of the neural basis of mathematical cognition do not place an emphasis on WM (e.g., Dehaene et al., 2003), a wide body of behavioral literature and a few recent neuroimaging studies suggest that domain-general factors, such as WM, play an important role in mathematical development (Dumontheil & Klingberg, 2011; Geary, 2011; Metcalfe et al., 2013). Understanding the role of domain-general factors, such as WM ability, is informative for future studies that will examine the neural underpinnings of arithmetic in children with poor arithmetic skills. A recent study by Ashkenazi and colleagues reported the relation of visual WM ability to the neural basis of addition to be weaker in children with math difficulties than their typically developing peers (Ashkenazi et al., 2013). Future studies could build on this finding by exploring the relation of both verbal and spatial WM ability to the neural basis of different arithmetic operations in diverse groups of children.

In sum, verbal and spatial WM ability are differentially linked to neural bases of multiplication and subtraction. For multiplication, higher verbal WM is more strongly related to greater recruitment of the left temporal cortex, but higher spatial WM is more strongly related to greater recruitment of right parietal cortex. Thus, our results suggest that, depending on their WM ability, children engage different neural systems that manipulate different representations to solve arithmetic problems.

ACKNOWLEDGMENTS

We thank Ilaria Berteletti for her comments on an earlier version of the article, and John V. Binzak and Rachna Mutreja for their assistance in data collection. We thank all participating children and their parents.

FUNDING

This research was supported by HD059177 from the National Institute of Child Health and Human Development to James R. Booth.

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