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PAPER

Parental socioeconomic status and the neural basis of arithmetic: differential relations to verbal and visuo-spatial representations

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Abstract

We examined the relation of parental socioeconomic status (SES) to the neural bases of subtraction in school-age children (9- to 12-year-olds). We independently localized brain regions subserving verbal versus visuo-spatial representations to determine whether the parental SES-related differences in children's reliance on these neural representations vary as a function of math skill. At higher SES levels, higher skill was associated with greater recruitment of the left temporal cortex, identified by the verbal localizer. At lower SES levels, higher skill was associated with greater recruitment of right parietal cortex, identified by the visuo-spatial localizer. This suggests that depending on parental SES, children engage different neural systems to solve subtraction problems. Furthermore, SES was related to the activation in the left temporal and frontal cortex during the independent verbal localizer task, but it was not related to activation during the independent visuo-spatial localizer task. Differences in activation during the verbal localizer task in turn were related to differences in activation during the subtraction task in right parietal cortex. The relation was stronger at lower SES levels. This result suggests that SES-related differences in the visuo-spatial regions during subtraction might be based in SES-related verbal differences.

Research highlights

- The relation between parental SES and the neural bases of subtraction in school-age children varies as a function of math skill.
- At higher levels of SES, higher skill is associated with greater recruitment of verbal regions, i.e. the left temporal cortex.
- At lower levels of SES, higher skill is associated with greater recruitment of visuo-spatial regions, i.e. right parietal cortex.
- SES-related differences are observed in recruitment of verbal regions during an independent verbal task. These differences relate to differences in activation in visuo-spatial areas during the subtraction task, suggesting that SES differences in visuo-spatial areas might be verbally based.

Introduction

Children from disadvantaged socioeconomic backgrounds are less likely to develop mathematics and reading proficiency, and are more likely to have a learning disability than their peers with higher socioeconomic status (SES) (Brooks-Gunn & Duncan, 1997; Duncan & Magnuson, 2012; NCES, 2011; NMAP, 2008). Large SES-related individual differences exist in children's math achievement starting from the early grades, and the differences tend to grow over time (NCES, 2011; Pungello, Kupersmidt, Burchinal & Patterson, 1996). Early differences in math achievement are significant in that they predict later academic achievement more strongly than early reading or socio-emotional skills (Duncan, Dowsett, Claessens, Magnuson, Huston *et al*., 2007; NMAP, 2008). However, nothing is

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known about the neural representations underlying SES-related disparities in math achievement. The goal of the present study is to use functional magnetic resonance imaging (fMRI) to examine the neural basis of the relation between parental SES and math skill. Specifically, we ask (1) how parental SES impacts reliance on brain regions that subserve verbal and visuo-spatial representations during basic arithmetic (e.g. single-digit subtraction), and (2) how the impact of parental SES on the neural basis of basic arithmetic varies as a function of children's math skill.

Existing behavioral studies suggest that SES might have stronger relations to verbal versus visuo-spatial representations underlying mathematics. SES-related differences in children's verbal skills are well described and they appear to be larger than differences in spatial skills (Hart & Risley, 1995; Hoff, 2003; Noble, McCandliss & Farah, 2007). In mathematical development, preverbal aspects of early mathematical cognition are considered to develop without instruction and verbal input (Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999; Feigenson, Dehaene & Spelke, 2004). Symbolic, later-developing verbal aspects of mathematical cognition depend upon environmental input and instruction (Jordan & Levine, 2009). SES-related differences are larger on verbal aspects of arithmetic, such as verbally presented number combinations or word problems, as compared to spatially represented, nonverbal tasks, such as nonverbal calculations with discs (Jordan, Huttenlocher & Levine, 1992; Jordan & Levine, 2009). Despite the behavioral evidence for stronger SES-related differences in verbal than spatial aspects of math achievement, children's reliance on verbal versus spatial neural representations as they are engaged in an arithmetic task have not been examined, so the question of how SES affects reliance on verbal versus spatial neural representations in basic arithmetic remains unanswered.

Neuroimaging studies can provide information about how the neural representations underlying mathematics are influenced by SES (Hackman & Farah, 2009; Raizada & Kishiyama, 2010). A growing number of neuroimaging studies reveal SES-related differences in neural activation patterns during verbal processing, executive function and reading tasks (for reviews see D'Angiulli, Lipina & Olesinska, 2012; Hackman & Farah, 2009; Nelson & Sheridan, 2011; Tomalski & Johnson, 2010). Structural imaging studies show that higher SES is positively related to gray matter volume and gyrification (Hanson, Hair, Shen, Shi, Gilmore *et al.*, 2013; Jednoróg, Altarelli, Monzalvo, Fluss, Dubois *et al.*, 2012; Noble, Houston, Kan & Sowell, 2012; Raizada, Richards, Meltzoff & Kuhl, 2008). SES differences on brain structure appear to be more pronounced for regions central to verbal processing and executive function, such as frontal, temporal and hippocampal areas, compared to the rest of the brain (Hair, Wolfe, Hanson & Pollak, 2013; Hanson, Chandra, Wolfe & Pollak, 2011; Hanson *et al.*, 2013; Noble *et al.*, 2012). Electrophysiological and functional imaging studies similarly suggest that the neural basis of verbal processing and executive function might be more efficient and specialized in higher SES children (Hackman & Farah, 2009; Pakulak, Sanders, Paulsen & Neville, 2005; Raizada *et al.*, 2008).

Recent research suggests that certain SES differences might only be detected if SES is examined as a moderator of brain–behavior relations (Hackman & Farah, 2009). In reading development, a recent study examined whether the SES-related differences in the neural basis of reading vary as a function of skill, i.e. among 7–10-year-old children with below-average phonological skill (Noble, Wolmetz, Ochs, Farah & McCandliss, 2006). Children at the lower end of the SES gradients showed a stronger relation between phonological awareness and activation in brain regions underlying verbal representations, i.e. left fusiform gyrus and perisylvian regions, than children at the higher end. The authors suggested that for higher SES children, rich environmental resources might have served to buffer low phonological skill. Children with lower phonological skill who might otherwise have been poor readers might have reached higher reading skills due to increased experience with print and letter–sound mappings. This might have resulted in weaker correlations between phonological skill and activation in reading-related regions in this group of higher SES children. This study focused on reading, which builds upon verbal representations, in a group of children with low skill. To our knowledge, no prior study examined how SES affects the neural basis of basic arithmetic, and whether it moderates brain–behavior relations in a group of children with a wider skill range.

Functional neuroimaging studies on basic arithmetic reveal a wide fronto-temporo-parietal network in adults and children. In solving arithmetical problems, individuals rely upon brain regions that underlie verbal representations, such as left lateral temporal cortex and inferior frontal cortex (Andres, Michaux & Pesenti, 2012; Andres, Pelgrims, Michaux, Olivier & Pesenti, 2011; Dehaene, Piazza, Pinel & Cohen, 2003; Lee, 2000; Prado, Mutreja, Zhang, Mehta, Desroches *et al.*, 2011). Brain regions that underlie spatial representations, such as right intra-parietal sulcus and posterior superior parietal cortex, are also recruited (Chochon, Cohen, van de Moortele & Dehaene, 1999; Lee, 2000; Prado *et al.*, 2011; Schmithorst & Brown, 2004). Activity in verbal regions might relate to retrieval of arithmetic facts, whereas activity in spatial regions might relate to procedural manipulation of numbers. Importantly, the neural basis of arithmetic seems to vary as a function of skill. A recent study (De Smedt, Holloway & Ansari, 2011) showed that for small addition and subtraction problems, 10–12-year-old children with lower math skill activated the right intraparietal sulcus to a greater extent than children with higher skill. The authors argued that low skill children might use procedural strategies (and rely on spatial neural representations), whereas higher skill children might retrieve arithmetical information from memory (and rely on verbal neural representations). However, it is unknown whether SES moderates brain–behavior correlations in children's reliance on verbal versus spatial neural representations during arithmetic. Given stronger SES-related differences in verbal aspects of mathematics (Jordan *et al*., 1992; Jordan & Levine, 2009), the relation between math skill and reliance on verbal neural representations might be stronger for higher SES children than lower SES children. In contrast, given their difficulties in verbal aspects of mathematics, higher skill children at the lower end of the SES continuum might rely to a greater extent on visuo-spatial representations than lower skill children.

In order to ask whether SES differentially affects reliance on verbal versus visuo-spatial neural representations during basic arithmetic, we measured brain activity of 9–12-year-old children while they evaluated single-digit subtraction problems, as well as during verbal and visuo-spatial localizer tasks. We used a word rhyming task to localize brain regions that subserve verbal representations. Previous literature has shown that this word rhyming task taps into verbal representations and successfully localizes regions underlying verbal representations in left temporo-parietal and inferior frontal cortices (Booth, 2010; Prado, Mutreja & Booth, 2014; Prado *et al*., 2011). We used a non-symbolic, dot comparison task to localize brain regions that subserve visuo-spatial representations. Previous literature has shown that this dot comparison task taps into spatio-numerical representations and successfully localizes regions involved in visuo-spatial representations in right intraparietal sulcus and superior parietal lobule (Prado *et al*., 2014; Prado *et al*., 2011). Importantly, performance on tasks similar to our verbal and visuo-spatial localizer tasks relates to mathematical skill (Halberda, Mazzocco & Feigenson, 2008; Hecht, Torgesen, Wagner & Rashotte, 2001; Krajewski & Schneider, 2009; Piazza, Facoetti, Trussardi, Berteletti, Conte *et al*., 2010; Siegel & Linder, 1984; Simmons, Singleton & Horne, 2008). We examined relations between SES and the neural bases of arithmetic in the verbal and spatial regions of interest (ROIs) identified by the localizer tasks. We also asked whether the SES differences in activation in verbal and visuo-spatial ROIs interact with children's math skill. Children's math skills were measured by a behavioral standardized measure of math fluency administered before scanning (Woodcock, McGrew & Mather, 2001).

High SES refers to a bundle of characteristics that include parental education, occupation, income and sometimes perceived social status, and it is associated with parental cognitive stimulation, access to education, high-quality neighborhoods, social networks, and reduced stress, among others (Bradley & Corwyn, 2002; Brooks-Gunn & Duncan, 1997; Duncan & Magnuson, 2012; Hackman & Farah, 2009). Because directly observing a family's SES is difficult, researchers typically use parental education, income or occupation or a combination thereof to measure SES. We used average education level of the parents as our measure of parental SES. Different components of SES are highly correlated with each other, but parental education tends to be more stable than income, is closely related to parent–child interactions and home learning environment, and is considered to be the strongest predictor of academic achievement (Duncan & Magnuson, 2012; Lewis & Mayes, 2012).

In sum, we examined (1) how parental SES impacts reliance on brain regions that subserve verbal and visuo-spatial representations during basic arithmetic (i.e. single-digit arithmetic), and (2) how the impact of parental SES on the neural basis of basic arithmetic varies as a function of children's math skill (i.e. math fluency). On the basis of the previous behavioral literature, we expected higher SES to be associated with greater reliance on verbal neural representations when solving basic arithmetic problems. We also expected the SES-related differences in the neural bases of basic arithmetic to vary as a function of mathematical skill. Specifically, we expected higher math skills to be associated with greater reliance on verbal neural representations when solving basic arithmetic, and the relation to be stronger at higher SES levels. Conversely, we expected a relation between math skill and reliance on visuo-spatial neural representations at lower SES levels.

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, 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).[1] 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 lobe), low behavioral accuracy in the scanner (i.e. lower than 35%) 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, mathematical and reading abilities. IQ was measured by the Verbal (Vocabulary, Similarities) and Performance (Block Design, Matrix Reasoning) subtests of the WASI (Weschler, 1999). Knowledge of arithmetical procedures was assessed with the Basic Calculations subtests of the CMAT (Hresko *et al*., 2003). The Basic Calculations subtests require children to solve increasingly difficult addition, subtraction, multiplication and division problems. Mathematical fluency was assessed by the Math Fluency subtest of the WJ-III (Woodcock *et al*., 2001). The Math Fluency subtest requires children to solve as many simple addition, subtraction, and multiplication problems as possible within a 3-minute period. Reading fluency was assessed by the Sight Word Efficiency and Phonemic Decoding Efficiency subtests of the TOWRE (Test of Word Reading Efficiency) which require children to pronounce words and phonemically regular nonwords accurately and fluently within a 5-minute period (Torgesen, Wagner & Rashotte, 1999). Table 1 summarizes children's performance on standardized tests.

[1] We used CMAT as a cut-off instead of WJ-III because CMAT is an untimed task whereas WJ-III is a timed task. The CMAT threshold served to include children who had a basic understanding of arithmetical facts, whereas the sample was allowed to vary in the speed/efficiency by which children reach these facts, as measured on WJ-III.

Table 1 *Performance on standardized tests and the subtraction task*

	Average (*SD*)
Standardized measures	
WASI Full-Scale IQ	116 (14)
TOWRE Reading Efficiency	109 (14)
WJ Math Fluency	102 (14)
CMAT Basic Calculation	119 (18)
Subtraction task	
Accuracy Small	0.90 (0.11)
Accuracy Large	0.86 (0.15)
Reaction time (ms) Small	1000 (304)
Reaction time (ms) Large	1123 (340)

Socioeconomic status

Parental education was used as a measure of socioeconomic status. The education level of the primary caregivers was measured categorically and each category was assigned a value equivalent to years of education (less than high school = 10 years, high school = 12 years, some college or associates degree = 14 years, college degree = 16 years, more than college = 18 years). The parents averaged 16.1 years of education (SD = 1.7, Range = 12–18). Education information for both mother and father was provided for 37 children, and for three children only mother's education information was provided. When information for both parents was present, the average of the two was taken. In other cases, the education level of the mother was used. Mother and father education level was significantly correlated with each other, $r = 0.43$, $p < .05$. The results reported below remained the same with the subset of 37 children whose both parents provided education information.

Arithmetic task

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 (see Figure 1A). Twenty-four number pairs were used, covering the full range of single-digit subtraction problems (with the exceptions below). 12 '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). The difficulty manipulation is based on an extensive literature on adults and children (Campbell & Xue, 2001; Levine, Jordan & Huttenlocher, 1992, Seyler, Kirk & Ashcraft, 2003). Each pair was repeated twice with a true answer (e.g. $5 - 3 = 2$) and once with a false answer. Thus,

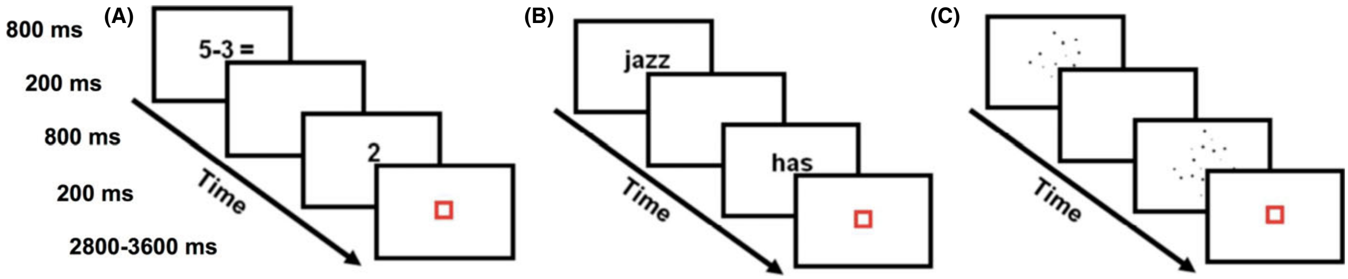

Figure 1 *Experimental tasks. (A) In the arithmetic problems, participants were asked to evaluate subtraction problems. Localizer tasks were used to identify the Regions of Interest. (B) In the verbal localizer task, participants decided whether two words rhymed or not. (C) In the visuo-spatial localizer task, participants decided which dot array included a larger number of dots.*

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 (see Figure 1B). 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 (24 similar, 24 not similar) and 48 word pairs were used in the practice session. In each trial of the visuo-spatial localizer, two dot arrays were sequentially presented (see Figure 1C). Children were asked to decide which of the two dot arrays was 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 (24 easy, 24 medium, 24 hard) and 36 pairs were used in the practice session. Average accuracy on the verbal localizer task was 84% (SD = 12) and average RT was 1135 ms (SD = 248). Average accuracy on the visuo-spatial localizer task was 88% (SD = 12) and RT was 972 ms (SD = 299).

Experimental procedure

After informed consent was obtained and standardized tests were administered, 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 three tasks in the mock fMRI scanner. The actual fMRI scanning session took place within one week of the practice session. In the fMRI scanner, subtraction and visuo-spatial localizer tasks were divided into two 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, dot array or word depending on the task) for 800 ms, followed by a blank screen for 200 ms. A second stimulus (subtraction, dot array or word, depending on the task) was presented for 800 ms, followed by a red fixation square presented for 200 ms. Participants were asked to make a response during an interval ranging from 2800 ms to 3600 ms. Twenty-four null trials were included in the subtraction and visuo-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 ms, 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 = 2000 ms. Before functional image acquisition, a high resolution T1-weighted 3D structural image was acquired for each subject (TR = 1570 ms, TE = 3.36 ms, 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) (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 ($4 \times 4 \times 8$ mm^3 full width at half maximum). Average movement in mm for translation and in radians for rotation was as follows: *x*-plane: $M = 0.13$, *y*-plane: $M = 1.04$, *z*-plane: $M = 0.21$, pitch: $M = 0.004$, roll: $M = 0.003$, yaw: $M = 0.07$. 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 2 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, Whitfield-Gabrieli, Reiss & Glover, 2007). 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, $2 \times 2 \times 4$ 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 (operands). Activation ended at the offset of the second stimulus (answer). The duration was 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. This was done to avoid contamination of activity by inhibitory processes associated with rejecting valid trials. The results reported remained the same when only correct responses were modeled. 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 SES, math fluency and neural bases of arithmetic, 2nd-level voxel-wise regression models were created. In each analysis, SES, math fluency scores, as well as the interaction between SES and math fluency score constituted the regressors of interest. In addition, we included full-scale IQ as a regressor of no interest. The analyses were conducted separately for each problem type (small, large). In order to examine the relations between SES and the neural bases of arithmetic, we identified the brain regions that showed an increase or a decrease in activity during the evaluation of small or large subtraction problems with respect to SES across subjects. In order to evaluate whether SES moderates the relation between math fluency and the neural bases of arithmetic, we identified brain regions that showed an increase or a decrease in activity during the evaluation of small or large subtraction problems with respect to the interaction term across subjects. For all analyses an implicit baseline of general task activation was used. All analyses were repeated with measures of performance on the arithmetic task, age and RT as regressors of no interest and the results reported below remained unchanged.

ROI definition

The relations of SES and math fluency to the neural basis of subtraction were examined within verbal and visuo-spatial ROIs, which 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). Visuo-spatial ROIs were identified using the visuo-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 visuo-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 visuo-spatial localizer contrast (Prado *et al*., 2011). A right-lateralized visuo-spatial mask was used based on previous literature suggesting that right parietal areas are more sensitive to visuo-spatial representations underlying arithmetic (Dehaene *et al*., 2003; Demir, Prado & Booth, 2014). Left parietal areas subserve verbally mediated representations of number and thus would not enable us to differentiate verbal versus visuo-spatial representations underlying arithmetic (Simon, Kherif, Flandin, Poline, Rivière *et al*., 2004). Although lateralized masks were used based on previous literature, the regions activated by the localizer tasks remained the same and significant using bilateral anatomical masks.

Statistical significance for the resulting verbal and visuo-spatial masks was defined using Monte Carlo simulations (using AFNI's AlphaSim program; http://afni.nimh. nih.gov/, with SPM's data smoothness parameters, FWHM = 7.9 8.2 14.7 mm). For verbal localizer, in order to reach corrected level threshold (alpha = 0.05), the clusters needed a voxel-level p-value of .05 and 183 voxels. For the visuo-spatial localizer, clusters needed a voxel-level p-value of .05 and 109 voxels. The verbal localizer contrast was associated with activity in the left MTG and STG, as well as in the left IFG (see Figure 2A and Table 2). The peak coordinates of left IFG and MTG were close to coordinates identified in previous studies using the same rhyming task (Euclidian distance of 14 mm for left IFG, 18 mm for left MTG) (Prado *et al*., 2011; Prado *et al*., 2014). These clusters constitute the verbal localizer mask. The visuo-spatial localizer contrast was associated with activity in one cluster spanning right SPL and IPL, which included the right IPS (see Figure 2B and Table 2). The peak coordinate of the cluster was close to coordinates identified in a previous study using the same task (Euclidian distance of 18 mm for right IPS) (Prado *et al*., 2014). These clusters constituted the visuo-spatial localizer mask. The pattern of results reported below remained the same when the procedure was repeated with anatomical masks only (i.e. without the

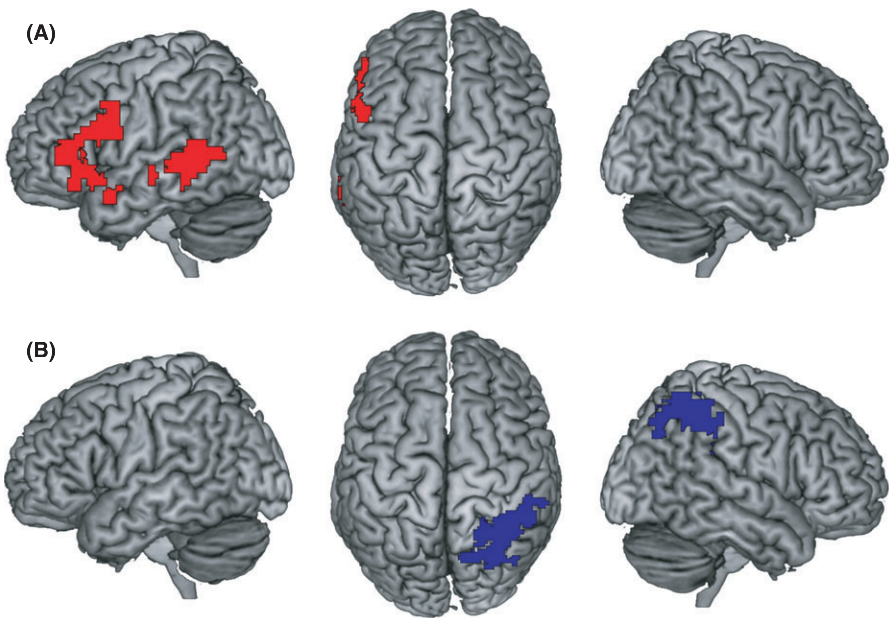

Figure 2 *Brain networks identified by the localizer tasks. (A) The verbal localizer task was associated with enhanced activity in a network that included left middle/superior temporal and inferior frontal gyrus. (B) The visuo-spatial localizer task was associated with enhanced activity in a network that included right inferior/superior parietal lobule. Activations are overlaid on a 3D rendering of the MNI-normalized anatomical brain. See Table 2 for full listing of coordinates.*

Table 2 *Peak activated voxels in the localizer tasks*

Anatomical location	~BA	MNI coordinates X	Y	Z	*z*-score	Size
Verbal localizer						
L. Middle / Superior Temporal Gyrus	21 / 22	−64	−46	6	4.09	398
L. Inferior Frontal Gyrus	9 / 45 / 46	−52	8	34	3.95	467
Visuo-spatial localizer						
R. Inferior / Superior Parietal Lobule, Intraparietal Sulcus	40 / 7	22	−64	54	5.38	712

Notes L., left; R. right; ~BA, approximate Broadmann Area for the peak coordinate; MNI, Montreal Neurological Institute; Size, number of 2 × 2 × 4 mm^3 voxels.

localizers) (verbal: left IFG, MTG and STG, visuo-spatial: right IPL and SPL).

ROI analyses

Statistical significance within each of these localizer and anatomical masks was defined using Monte Carlo simulations (using AFNI's AlphaSim program; http://afni.nimh. nih.gov/). For subtraction task analyses, in order to reach corrected level threshold (alpha = 0.05) within the verbal ROIs, the clusters needed a voxel-level *p*-value of .05 and 57 voxels. For the visuo-spatial ROIs, clusters needed a *p*-value of .05 and 64 voxels.

Whole-brain analysis

To investigate non-predicted effects in regions outside verbal or visuo-spatial ROIs, we also report results of whole-brain analyses. Effects outside of hypothesized ROIs are reported at a height threshold of $p < .05$, spatial extent threshold of $p < .05$, FWE corrected for multiple comparisons.

Results

Task performance

Table 1 summarizes children's behavioral performance on the subtraction task. Overall, SES and math fluency were not significant predictors of children's behavioral performance on the subtraction task. A repeated measures ANOVA on subtraction accuracy with problem size (small, large), SES and math fluency as independent variables revealed no significant main effects of size, $F(1, 37) = 2.34$, $p = .14$, SES, $F(1, 37) = 1.34$, $p = .26$, or math fluency, $F(1, 37) = .1.57$, $p = .22$. Similarly, the three-way interaction between size, SES and math fluency, $F(1, 37) = 1.50$, $p = .23$, and the two-way interactions did not reach significance (size × SES, $F(1, 37) = 1.66$, $p = .21$, size × math fluency, $F(1, 37) = 2.02$, $p = .16$, SES × math fluency, $F(1, 37) = .95$, $p = .34$). A repeated measures ANOVA on subtraction reaction time with problem size (small, large), SES and math fluency as independent variables revealed no significant main effects of size, $F(1, 37) = .93$, $p = .34$, SES, $F(1, 37) = 0.26$, $p = .61$, or math fluency, $F(1, 37) = .21$, $p = .65$. The three-way interaction between size, SES and math fluency, $F(1, 37) = 1.30$, $p = .26$, and the two-way interactions did not reach significance (size × SES, $F(1, 37) = 1.07$, $p = .32$, size × math fluency, $F(1, 37) = 1.28$, $p = .27$, SES × math fluency, $F(1, 37) = .27$, $p = .61$). SES was significantly correlated with full-scale IQ, $r = .35$, $p = .03$, but not with math fluency, $r = .04$, $p = .79$, CMAT, $r = .19$, $p = .24$, or TOWRE, $r = .11$, $p = .55$. Thus, full-scale IQ was entered as a variable of no-interest in the 2nd-level voxel-wise regression analyses described below. Furthermore, SES was not significantly correlated with the localizer task accuracy (verbal: $r = 0.29$, $p = .07$, visuo-spatial: $r = -0.16$, $p > .10$) or RT (verbal: $r = 0.24$, $p > .10$, visuo-spatial: $r = -0.22$, $p > .10$). The correlation between math fluency and IQ was not significant ($r = .13$, $p > .10$).

Overall activation in verbal and visuo-spatial ROIs during the subtraction task

We first examined overall activation in the verbal and visuo-spatial ROIs during the subtraction task, using contrast of [small trials − baseline] and [large trials − baseline] submitted to one-sample *t*-tests across all participants. In verbal ROIs, small problems showed significant activation in left IFG (peak coordinate: x = −52, y = 4, z = 38, BA = 9, $z = 3.72$, k = 103 voxels), and in left MTG (peak coordinate: x = −46, y = −44, z = 6, BA = 22, $z = 2.90$, k = 109 voxels) as compared to baseline. Large problems showed significant activation in left IFG (peak coordinate: x = −48, y = 6, z = 34, BA = 9, $z = 3.93$, k = 134 voxels), and in left MTG (peak coordinate: x = −48, y = −42, z = 6, BA = 22, $z = 3.45$, k = 197 voxels) as compared to baseline. In addition, in visuo-spatial ROIs, small problems showed significant activation in right IPS (peak coordinate: x = 42, y = −42, z = 46, BA = 40, $z = 3.23$, k = 317 voxels) as compared to baseline. Large problems significantly activated right IPS (peak coordinate: x = 34, y = −62, z = 46, BA = 7/40, $z = 3.87$, k = 385 voxels).

No overall parental SES-related differences in brain activity during the subtraction task

We then examined the relation between SES and the neural basis of small or large subtraction problems using 2nd-level voxel-wise regression analyses (see Methods). We identified the brain regions within our verbal or visuo-spatial ROIs where activity during the evaluation of small or large subtraction problems was associated with SES (when the effects of IQ and math fluency are controlled). The contrasts of interest were [small trials versus baseline] and [large trials versus baseline]. There were no significant clusters within the verbal or visuo-spatial ROIs that were positively or negatively associated with SES for small or large subtraction problems.

Math fluency-related differences in brain activity during the subtraction task

We also examined the relation between math fluency and the neural basis of small or large subtraction problems using 2nd-level voxel-regression analyses (see Methods). We identified brain regions within our verbal and visuo-spatial ROIs that showed a significant association with math fluency when effects of IQ and SES are controlled. There were no significant clusters that were positively related to math fluency in verbal or visuo-spatial ROIs for large problems. For small problems, there was a trend in the direction of math fluency being negatively related to activation in right IPS (peak coordinate: x = 44, y = −36, z = 42, BA = 40, z = 2.60, p = .07, k = 59 voxels).

Parental SES moderates relation of math fluency to brain activity during the subtraction task

We then examined whether SES moderates the relation of math fluency to the neural basis of small or large subtraction problems using 2nd-level voxel-wise regression analyses (see Methods). We identified the brain regions within our verbal or visuo-spatial ROIs where activity during the evaluation of small or large subtraction problems was associated with the interaction term (when the effects of IQ are controlled).

Verbal ROIs

There were no significant clusters within the verbal ROIs that were associated with the interaction term for small subtraction problems. For large subtraction problems, we found a significant interaction term in a cluster in left MTG (peak coordinate: x = −64, y = −48, z = −2, BA = 21, z = 2.85, k = 62 voxels) (see Figure 3A). For visualization purposes only, we divided the children into two groups based on median SES, 16 years (lower than or at the median constituting lower SES, and higher than the median constituting higher SES). We then extracted the average beta weight from the significant cluster, and plotted it against math fluency for the two SES groups.

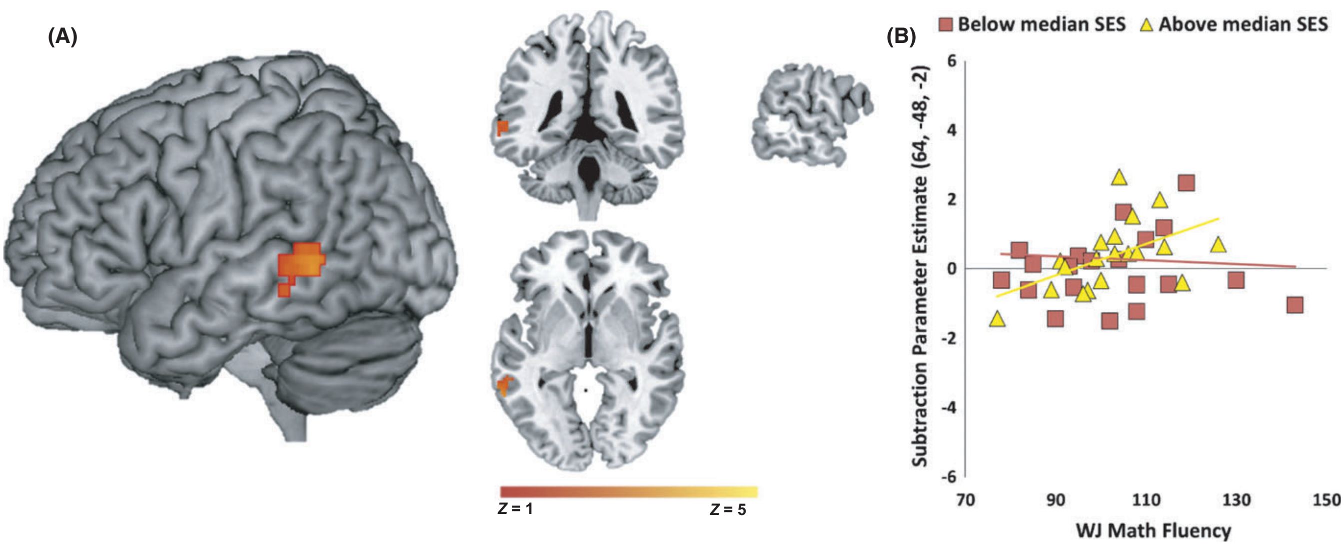

Figure 3 *Interaction between SES and fluency in the verbal ROI for large subtraction problems. (A) Activity in left middle temporal gyrus (MTG) showed a SES and fluency interaction. Activation is overlaid on a 3D rendering and on coronal, sagittal, and axial slices of MNI-normalized anatomical brain (x = −62, y = −42, z = 2). (B) Average brain activity was extracted from the significant cluster in left MTG, and plotted against math fluency scores for visualization purposes only. Relation was visualized for children above the median SES and below the median SES.*

This plot showed that for higher SES math fluency appears to be positively associated with activity during subtraction in left MTG, but the relation appears to be flat for lower SES (see Figure 3B).

Visuo-spatial ROIs

There were no significant clusters within the visuo-spatial ROIs that were positively associated with the interaction term for large subtraction problems. However, we found a significant interaction term in a cluster in right IPS for small problems (peak coordinate: x = 30, y = −60, z = 58, BA = 7/40, z = 2.74, k = 87 voxels) (see Figure 4A). Similar to previous analyses, for visualization purposes, we divided the children into two groups based on median SES. We then extracted the average beta weight from the significant cluster, and plotted it against math fluency for the two SES groups. This plot showed that for higher SES children fluency appears to be negatively associated with activity during subtraction in right IPS, but the relation between fluency and activation in right IPS appears to be positive for low SES children (see Figure 4B).

Parental SES-related differences during the verbal localizer task, and their relations to activation in visuo-spatial regions during the subtraction task

As predicted, at higher levels of SES, higher math fluency was associated with stronger reliance on left MTG and weaker reliance on right IPS. At lower levels of SES, higher fluency was associated with stronger reliance on right IPS. Previous literature suggests that the relation between SES and math performance may be rooted in differences in children's verbal skills (Jordan *et al*., 1992; Jordan & Levine, 2009). In the context of our study, this argument would predict (1) SES differences in activation during the independent verbal localizer task, and (2) relations between verbal localizer task activation and subtraction task activation.

In order to test whether there are SES-related differences in children's verbal neural representations, we first conducted similar 2nd-level voxel-wise regressions on the verbal and visuo-spatial localizers (see Methods). We identified brain regions within our verbal and visuo-spatial anatomical ROIs that showed a significant association with SES (when effects of IQ are controlled). There were no brain areas where activation was related to SES in the visuo-spatial localizer task. In the verbal localizer task, however, SES was negatively related to activation in two clusters in left MTG (peak coordinate, x = −48, y = −42, z = 10, BA = 21, z = 3.82, k = 339 voxels) and left IFG (peak coordinate, x = −38, y = 20, z = −6, BA = 47, z = 3.93, k = 368 voxels) (Figure 5A).

Second, we examined whether activation during the independent verbal localizer relates to activation during subtraction task. If SES-related differences in the relation between math fluency and subtraction in the visuo-spatial ROIs are based on differences in verbal representations, then verbal localizer task activation

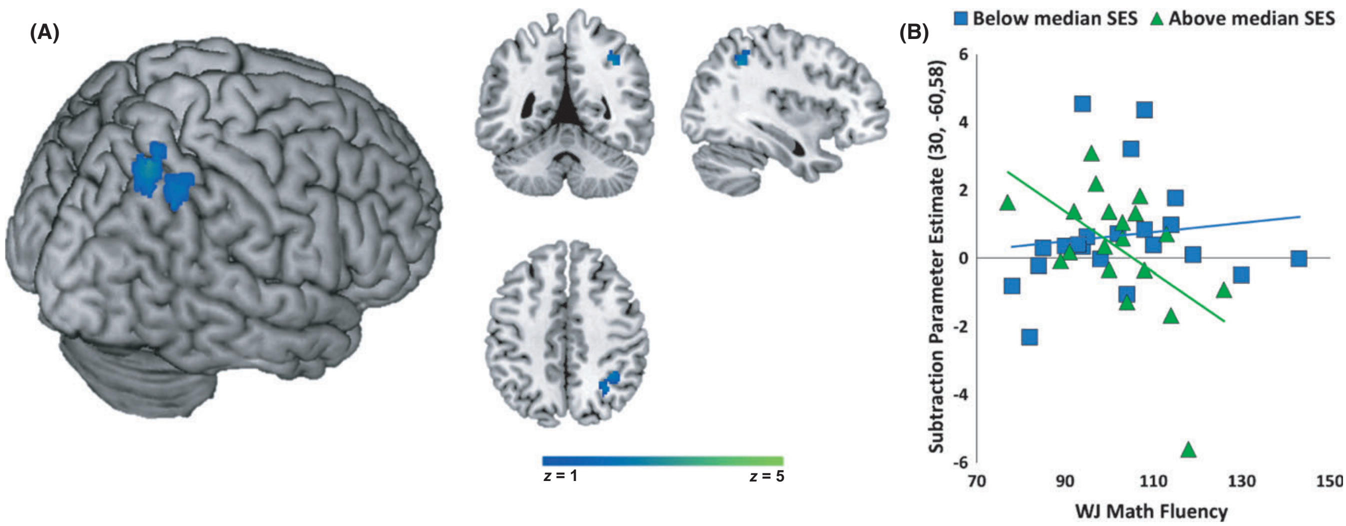

Figure 4 *Interaction between SES and fluency in the visuo-spatial ROI for small subtraction problems. (A) Activity in right intraparietal sulcus (IPS) showed a SES and fluency interaction. Activation is overlaid on a 3D rendering and on coronal, sagittal, and axial slices of MNI-normalized anatomical brain (x = 38, y = −52, z = 45). (B) Average brain activity was extracted from the significant cluster in right intra-parietal sulcus (IPS), and plotted against math fluency scores for visualization purposes only. Relation was visualized for children above the median SES and below the median SES.*

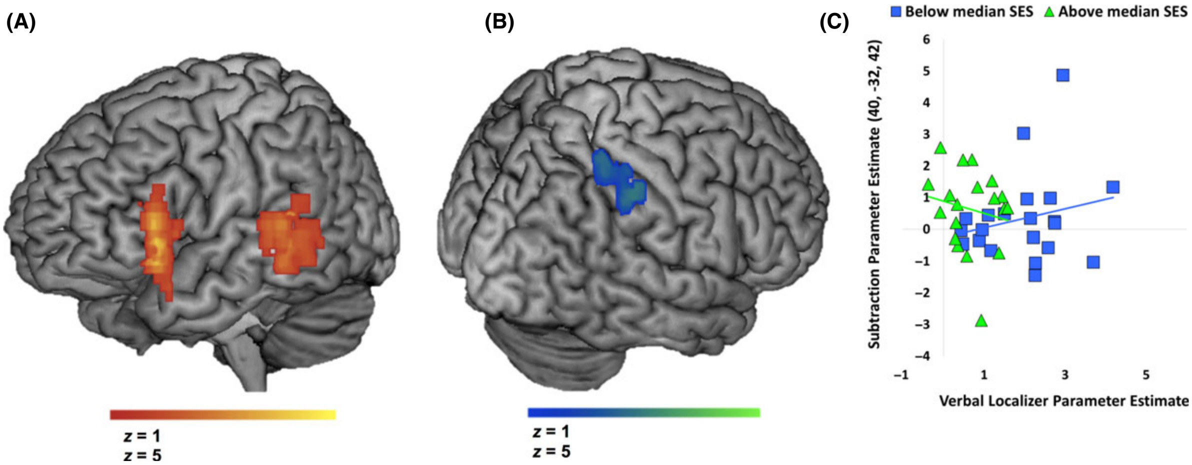

Figure 5 *Relation of activation in verbal localizer task to subtraction. (A) Activity in left middle temporal gyrus (MTG) and inferior frontal gyrus (IFG) showed a negative relation to SES in the verbal localizer task. Activation is overlaid on a 3D rendering of MNI-normalized anatomical brain. (B) Activity in right intraparietal sulcus (IPS) during subtraction was related to the interaction between SES and average IFG/MTG activation during the verbal localizer. (C) Average brain activity was extracted from the significant clusters in MTG/IFG during the verbal localizer, and plotted against the significant cluster in right IPS during subtraction separately for children above the median SES and below the median SES, for visualization purposes only.*

should relate to activation in the visuo-spatial ROIs in the subtraction task. To examine this relation, we extracted the average beta weight from the two clusters that showed a significant negative association with the SES in the verbal localizer task. This served as our measure of SES-related activation differences in the verbal localizer task. We then included the average beta weight from these clusters as a predictor in 2nd-level voxel-wise regression analyses on the subtraction task activation, using IQ and SES as covariates. We also included an interaction term between the verbal localizer cluster activation and SES. Activation during the verbal localizer was related to right IPS activation in the subtraction task and this relation varied as a function of SES (peak coordinate: x = 40, y = −32, z = 42, BA = 40, $z = 2.82$, k = 144 voxels). The significant cluster overlapped with the cluster in right IPS found to be significantly correlated with SES × WJ fluency interaction during the subtraction task (see Figure 5B). Similar to previous analyses, for visualization purposes, we divided the children into two groups based on median SES. We plotted the average beta weight from the significant cluster in the right IPS during subtraction against left MTG activation in the verbal localizer for the two SES groups. This plot showed that for lower SES children left MTG activation during the verbal localizer task is positively associated with activity during subtraction in right IPS, but the relation between left MTG activation during the verbal localizer and activation in right IPS during subtraction is flat for higher SES children (see Figure 5C).

Whole-brain analysis

No significant SES or SES × math fluency effects were observed outside the hypothesized ROIs.

Discussion

A growing number of neuroimaging studies report SES disparities on the neural basis of cognitive development. They provide an emerging picture of the underlying neural representations that are influenced by environmental experiences (D'Angiulli *et al*., 2012; Hackman & Farah, 2009; Tomalski & Johnson, 2010). Our study adds to this existing literature by reporting, to our knowledge for the first time, SES gradients in the neural bases of basic arithmetic. We independently identified verbal and visuo-spatial neural representations, and examined how SES affects reliance on these neural representations as children are solving basic arithmetic problems (e.g. single-digit subtraction). We also asked whether SES moderates relations between the neural bases of arithmetic and math skill.

We showed that parental SES did not relate to brain activity during subtraction independent of skill. Rather, it moderated the relations between math skill and the neural bases of arithmetic. At higher SES levels, math skill was positively related to greater reliance on verbal ROIs, specifically left middle temporal gyrus. Left temporo-parietal cortices are widely thought to support verbal representations, such as representations of the associations between words (Blumenfeld, Booth & Burman, 2006; Booth, Burman, Meyer, Gitelman, Parrish *et al.*, 2002; Fiebach, Friederici, Müller & von Cramon, 2002). In arithmetic, left middle temporal gyrus activation is thought to reflect the strength of associations between problems and their solutions (Prado *et al.*, 2011). Thus, SES-related increases of activity for higher fluency children in left middle temporal gyrus might reflect stronger verbal representations of associations between problems and their answers. We did not find SES-related differences in left IFG. Previous studies associated activation of left IFG with effortful control and retrieval of semantic knowledge (Bookheimer, 2002) as well as selection between competing representations (Badre & Wagner, 2007). Left IFG might be more involved in manipulation of verbal representations that are hosted in left MTG. Although it is hard to interpret a null finding, our results might suggest that the environmental input higher SES children receive might influence mathematical performance specifically through the quality of verbal representations in left MTG, rather than the manipulation of these representations in left IFG.

Why might higher SES children have stronger verbal representations? Starting from the preschool years, children differ widely from each other in terms of their exposure to verbal input in general and verbal input about mathematics specifically, both at home and in preschool. The quantity and quality of this input varies along the SES gradient (Blevins-Knabe & Musun-Miller, 1996; Ehrlich, 2007; Gunderson & Levine, 2011; Hart & Risley, 1995; Hoff, 2003; Levine, Suriyakham, Rowe, Huttenlocher & Gunderson, 2010; Saxe, Guberman, Gearhart, Gelman, Massey *et al.*, 1987). For example, SES is positively correlated with the quantity of parental number talk during naturalistic parent–child interactions during preschool years (Gunderson & Levine, 2011). Furthermore, parental verbal input strongly relates to preschool numerosity outcomes, more strongly than parental numerosity-related activities (Anders, Rossbach, Weinert, Ebert, Kuger *et al.*, 2012; Gunderson & Levine, 2011). Thus, starting from earlier ages, higher SES children might develop stronger verbal representations in general and stronger verbal representations of numerical quantities more specifically, for example between Arabic numbers and their meaning. When learning arithmetic problems, the stronger verbal representations higher SES children built might enable them to form stronger associations between problems and their solutions. In our study, the higher the SES, the lower was the engagement of brain regions subserving verbal representations, e.g. left temporal cortex, during the independent verbal localizer task. Previous studies suggest that neural basis of verbal processing and executive function might be more efficient and specialized in higher SES children (Hackman & Farah, 2009; Pakulak *et al.*, 2005; Raizada *et al.*, 2008). Thus, SES-related differences in mathematics might be rooted in strength of children's verbal representations. Supporting this view, interventions aiming to improve mathematical cognition in low SES children have been reported to improve performance on verbal aspects of math, e.g. comparison of number words, but not non-symbolic, spatial aspects, e.g. comparison of magnitudes (Wilson, Dehaene, Dubois & Fayol, 2009).

Our findings revealed a different profile for the children at the lower end of the SES continuum in that higher fluency children activated visuo-spatial ROIs, specifically right intra-parietal sulcus, to a greater degree. The right intra-parietal sulcus has been shown to underlie spatial representations (Cavanna & Trimble, 2006; Smith & Jonides, 1997). In arithmetic, activation in right intra-parietal sulcus is observed when adults report using spatial representations of numerical quantities to solve problems (Delazer, Domahs, Bartha, Brenneis, Lochy *et al.*, 2003; Grabner, Ansari, Koschutnig, Reishofer, Ebner *et al.*, 2009; Ischebeck, Zamarian, Egger, Schocke & Delazer, 2007). Performance on arithmetic problems at any age is a mixture of multiple approaches, including retrieval of verbal representations and manipulation of spatial representations of numbers (Lemaire & Siegler, 1995; Siegler, 1988). Although children are assumed to move from procedural to retrieval strategies with experience, this hypothesis has been recently contested and both strategies are likely to continue well into adulthood (Fayol & Thevenot, 2012; LeFevre, Sadesky & Bisanz, 1996; Prado *et al.*, 2014). The specific strategy used might depend on the effectiveness of the strategy for the problem solver (Lemaire & Siegler, 1995; Siegler, 1988). We show here that the strategy taken might depend on the environmental experiences of the learner as well as their skill. In the absence of the environmental support that higher SES children receive, lower SES children might use quantity-based, procedural strategies. Similarly, Jordan and colleagues showed that low SES children start using procedural strategies, such as counting fingers, later than their higher SES peers in kindergarten and continue using such strategies longer than them (Jordan, Kaplan, Ramineni & Locuniak, 2008).

Our study offers further insights into why children differ in the neural representations they recruit during subtraction as a function of parental SES. Our results showed that the lower the SES, the greater was the engagement of the brain regions subserving verbal representations during an independent verbal localizer task. This finding supports previous neuroimaging studies showing strong SES differences on verbal tasks (Hackman & Farah, 2009; Pakulak *et al*., 2005; Raizada *et al*., 2008). We did not find SES-related effects in an independent spatial localizer task. Furthermore, SES-related differences in activation during the verbal localizer task were related to recruitment of visuo-spatial neural representations in the subtraction task, specifically at the lower end of the SES continuum. For children with lower SES levels, the more they engaged verbal regions during the verbal localizer task, the greater the reliance on visuo-spatial representations during the subtraction task. We interpret these results to suggest that lower SES children's weaker verbal representations might result in using spatial strategies and not verbal strategies during subtraction (De Smedt *et al*., 2011). This is consistent with behavioral literature examining SES differences in the verbal input children receive and in children's own performance on verbal aspects of math (Ehrlich, 2007; Gunderson & Levine, 2011; Jordan *et al*., 1992; Jordan & Levine, 2009). Together with this literature, our results suggest that children's reliance on spatial neural representations at the lower end of the SES continuum was a product of their differences in the nature of verbal representations.

SES-related differences in the nature of verbal representations could also explain our finding suggesting that SES and math skill effects vary as a function of problem size. The interaction between SES and math skill in the verbal ROIs was significant for large, but not for small, problems. In contrast, interaction between SES and math skill in visuo-spatial ROIs was significant for small, but not large, problems. Previous literature has suggested that due to differential exposure and practice, small problems are usually solved through verbal retrieval, whereas larger problems are solved through procedural strategies (Campbell & Xue, 2001; LeFevre *et al*., 1996; Ashcraft, 1992; Prado, Lu, Liu, Dong, Zhou *et al*., 2013). Due to their rich verbal representations, higher SES children who are more highly skilled might be able to form verbal associations even between the operands and the answers for large problems and verbally retrieve the answers to such less-frequent and less-practiced problems. This would explain our finding of the dependency of SES differences on math skill in verbal ROIs for large problems. Due to poorer verbal representations, lower SES children might have difficulty forming verbal associations between small numbers; thus, they might be more likely use procedural strategies instead for these highly practiced problems. This could explain our finding of the dependency of SES differences on math skill in visuo-spatial ROIs for small problems.

Whether SES-related differences in brain structure and function should be interpreted to indicate delays, deficits or adaptations is currently under discussion (D'Angiulli *et al*., 2012; Demir & Küntay, 2014, Hackman & Farah, 2009; Hoff, 2013, Blair & Raver, 2012). In the context of our study, children's behavioral performance on single-digit arithmetic problems did not vary according to SES. However, SES-related differences in math achievement are well established (NCES, 2011; NMAP, 2008). What the long-term implications are of reliance on spatial neural representations by higher skill lower SES children remain an open question. Future longitudinal studies should explore which early neural organizations are associated with optimal behavioral outcomes.

One limitation of the present study is that our sample had a rather restricted range of parental SES. This homogeneity allowed us to examine SES-related differences in the neural basis of arithmetic without SES-related differences in behavioral measures, which could confound neural effects with differences due to accuracy or motivation. Future studies should examine SES-related differences using a finer-grained measure of parental SES. Parental education is considered the strongest predictor of academic achievement, but current results should also be confirmed using a wider range of SES indicators, including income and occupation. Using a less restricted and a more comprehensive SES measure as well as a larger sample size might lead to stronger effects than the ones observed in the current study. Furthermore, future studies should examine SES-related differences in neural activation during other basic arithmetic tasks, such as addition or multiplication and more complex mathematics tasks, such as math word problems, which heavily rely on verbal representations as well as visuo-spatial representations.

In sum, our goal was to examine the relations between parental SES and the neural basis of subtraction in school-age children. We found, for the first time, that the parental SES-related differences in the neural basis of subtraction varied as a function of math skill. The higher the SES, the stronger was the association between skill and reliance on verbal neural representations, i.e. recruitment of left temporal cortex. At the lower end of the SES continuum, higher skill was associated with greater reliance on visuo-spatial neural representations and recruitment of right parietal cortex. Lower SES children showed a greater amount of activation in left temporal and frontal cortex on an independent verbal task. The variability in activation in left temporal cortex during the independent verbal localizer task related to the differences in activation in right parietal cortex during subtraction, specifically at the lower SES levels. Results suggest that the relations between parental SES and the use of verbal and visuo-spatial neural representations during subtraction depend on children's math skill, but that SES-related differences in visuo-spatial neural representations might be verbally based.

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