Published in final edited form as:

Magn Reson Imaging. 2009 November ; 27(9): 1187–1197. doi:10.1016/j.mri.2009.05.010.

The Neural Correlates of Calculation Ability in Children: An fMRI Study

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Abstract

Most studies investigating mental numerical processing involve adult participants and little is known about the functioning of these systems in children. The current study used functional magnetic resonance imaging (fMRI) to investigate the neural correlates of numeracy and the influence of age on these correlates with a group of adults and a group of third graders who had average to above average mathematical ability. Participants performed simple and complex versions of exact and approximate calculation tasks while in the magnet. Like adults, children activated a network of brain regions in the frontal and parietal lobes during the calculation tasks, and they recruited additional brain regions for the more complex versions of the tasks. However, direct comparisons between adults and children revealed significant differences in level of activation across all tasks. In particular, patterns of activation in the parietal lobe were significantly different as a function of age. Findings support previous claims that the parietal lobe becomes more specialized for arithmetic tasks with age.

Keywords

arithmetic; fMRI; mathematical skill; numerical processing; school-age

The development of numerical competence is strongly related to an individual's level of independence, productivity, and employment [1]. In contrast to literacy, much less is known about numeracy at the level of the brain and behavior even though difficulties with math occur as frequently as reading difficulties [2]. Most studies of the neural correlates of numeracy have involved adults. These studies include neuropsychological studies of brain-injured adults with acalculia and functional imaging studies of adults who are mathematically competent. Initial evidence of the neural correlates of calculation arose from lesion studies in which the type of mathematical processing deficit exhibited by a patient was found to vary with the anatomical location of the brain lesion [3-5]. A theory that two overlapping systems existed for numerical processing emerged from these studies [6-7]. One system corresponds to the capacity to represent distinct quantities exactly. This system is highly reliant on accurate and fluent retrieval of mathematical facts. The second system involves the capacity to estimate and judge approximations of numerical magnitude. Interpretation of results from lesion studies is limited

for several reasons. In particular, brain trauma typically encompasses large anatomical regions, limiting the specificity with which one can link a particular brain region to a deficient cognitive process. A more specific view of the neuronal anatomy underlying the cognitive processes that support calculation skill has since been attained via the application of functional imaging. Functional evidence supports the existence of the two numerical processing systems identified with the lesion studies [8-9]. However, evidence for a single, overlapping system has also been reported [10], especially when the complexity level of a task is considered (or the perceived complexity level based on participant proficiency at the task [11]).

Imaging studies frequently use single digit exact and approximate calculation tasks to explore the functional characteristics of the two systems for numerical processing identified in the lesion studies. A functional network comprising bilateral parietal cortex, dorsolateral and inferior frontal gyri, and the anterior cingulate is frequently reported as activated in adult participants during numerical tasks. The two types of tasks employ distinct cognitive strategies, which elicit different patterns of activation from the brain regions comprising the functional network [3,6,9]. For example, adults tend to acquire exact calculation knowledge in language-specific format. As a result, performance is associated with activation in functional regions specialized for linguistic processes such as the left hemisphere perisylvian regions [9]. Nonverbal strategies can also be employed to solve simple exact calculation problems [12]. Type of strategy employed is indicated by the location of parietal lobe activation: Math facts learned by rote and retrieved from verbal memory activate the angular gyrus [3,6,9]. In contrast, greater activation of the intraparietal sulcus (IPS) is seen when nonverbal strategies are employed [7]. Greater bilateral activation of the IPS is also seen during approximate calculation, which requires an understanding of *proximity* or knowledge about the location of numbers on a mental number line. While simple exact and approximate calculation have distinct functional patterns, Stanescu-Cosson et al. [11] found that as task complexity levels increased, adult participants recruited virtually identical brain areas to perform the two tasks. From these results Stanescu-Cosson and colleagues [11] hypothesized that the “networks for exact and approximate processing are not mutually exclusive, but are functionally integrated and are co-activated when solving difficult problems.”

Compared with the number of published studies investigating the existence of these two numerical processing systems in adult participants, relatively few have been performed with young children. Available findings suggest that a large degree of functional overlap is seen in location of the adult and child cortical activations [13-17]. The level of activation within these brain regions correlates with participants' age, a reflection of the groups' differences in cognitive processing abilities [18]. For example, children have increased activation in the prefrontal regions that likely results from the allocation of a greater amount of cognitive resources to executive functioning and working memory processes for mathematical task completion. A decrease in prefrontal lobe activation occurs with age [18], which reflects changes in the calculation processing demands from more effortful to more automatic [19-20]. A major influence on this functional change is the learning that occurs through educational instruction. Mathematical knowledge is particularly influenced by quantity and quality of instruction, and Kucian et al. (2008) reported that functional differences between adults and children during simple arithmetic tasks were associated with a specialization for mathematical skill that occurs with schooling. Previous functional magnetic resonance imaging (fMRI) studies investigating the neural correlates of number comparison [13-14] and calculation [16-18] in school age children combined different grade-levels in their sample of participants. Therefore, it is important to study the neural correlates of calculation ability in a group of children in the same grade level at school.

The aim of the present study was to evaluate the neural correlates of exact and approximate calculation ability in adults and in a group of children in third grade with average to above

average mathematical ability. Based on results from previous studies, we hypothesized that children and adults would recruit similar networks to perform the two types of tasks. In view of the results of Rivera et al. [18], we predicted that children and adults would differ in the level of activation in the frontal and parietal cortices. We also investigated the issue of complexity and proficiency by using simple and complex versions of exact and approximate calculation tasks. We hypothesized that comparisons between the complex and simple versions of the tasks, regardless of the type of task, would reveal increased activation in the prefrontal brain regions that children use to solve more difficult problems.

Materials and Methods

Participants

The participants included 10 adults and 27 children. Adults comprised five males and five females who ranged in age from 25 to 49 years (mean age 30.7, $SD = 7.3$). Children comprised 13 boys and 14 girls, ranging in age from 7.1 to 9.4 years (mean age = 8.1, $SD = 0.4$). Third grade is an ideal time to investigate exact and approximate calculation tasks because basic skills that support these tasks are taught in first and second grade, creating a range of skill development by third grade. Children were recruited over a period of two years from a larger study investigating the effects of mathematics instruction. To be included in the present study, children had to perform in the average to above average range on a calculation screening measure administered in the larger study and to receive all math instruction in the regular classroom. Average ability was defined as a score at or above the 49th percentile on the screening measure. A high ability was used as a cut-off for the current study to ensure that participants had good calculation skills [see 21]. Imaging data were collected from January to July on 35 children. Due to movement artifacts or failure to complete the in-magnet tasks, eight children were removed from analyses. High resolution magnetic resonance scans indicated that none of the participants had any overt neuroanatomical abnormality. This study was approved by the Vanderbilt University Institutional Review Board. Written informed consent was obtained from all children's guardians. Written assent was obtained from the children.

Screening Measure

Behavioral tests were not administered to the adults. As part of their screening process for inclusion in the larger study, trained examiners administered the calculation subtest of the Wide Range Achievement Test – Third Edition (WRAT-3) to children during the first semester of their third-grade year. The WRAT-3 is a broadly used standardized measure of achievement. The calculation subtest involves the identification of numbers and computations that increase in difficulty. Children had a mean standard score of 109.07 ($SD = 5.8$) on this subtest. The subtest means were higher than the expected average of 100 because we excluded students with percentile scores below 50.

Experimental Design and Procedure

Imaging stimuli and task—Children performed the imaging tasks on a computer outside of the MRI scanner to acclimate them to the structure and speed of the tasks. A subset of each task with novel equations was used for these practice sessions. Children were put in a mock scanner to simulate the in-magnet environment and to introduce them to the various noises made by the magnet. After completing the practice sessions, children performed the experimental tasks in the magnet scanner. Adults were familiarized with task stimuli and instructions prior to scanning, but practice sessions were not administered due to the relative ease of the math problems. All adults reported being comfortable with the fMRI environment and did not use the mock scanner.

During the scanning procedure, participants lay supine in the MRI, looking up at a mirror that reflected a screen on which computer-controlled stimuli were projected using E-Prime software (Psychology Software Tools, Inc.). At the beginning of each trial, participants saw a screen with written instructions, and the examiner read these instructions aloud to the participants. The imaging paradigm was a standard blocked design. Each functional imaging run was five min in duration and consisted of three 40 s blocks of each experimental task (four experimental tasks total, a single and a double digit exact calculation tasks and a single and a double digit approximate calculation tasks), three 40 s blocks of the control task (Greek letter matching task) and three 20 s blocks of rest (Figure 1). The calculation tasks were derived from Dehaene et al. [9]. All task items were presented vertically with three response choices shown horizontally at the bottom. Participants chose the correct answer by pressing a button (on a MRI compatible response pad) corresponding to the location (left, middle, right) of the correct response. The items and response choices remained on the screen until the participant responded or the block ended after 40 s. Numeric and control tasks were self-paced; therefore, the number of trials that participants completed within each block varied. Rogers, Anderson, Gatenby, Cannistraci, and Gore [22] demonstrated that paced and self-paced versions of the same mathematical task place comparable demands on calculation-specific and comparison-specific brain regions. Task presentation was randomized across all participants, and items were randomized within each block. In all trials, when not actively engaged in a task, participants were instructed to fixate on a gray square on the screen.

A Philips 3 Tesla Achieva (Philips Healthcare Inc.) was used to acquire the MRI data. Anatomical scans were acquired for approximately 15 min prior to functional scans. The anatomical images were acquired with a T-1 weighted, 3D turbo field echo pulse sequence (170 slices, 1 mm³ voxels). A high-resolution 2D T1 anatomical series was also acquired at the same location and slice thickness as the functional data. All functional data for child participants were acquired using a gradient echo EPI sequence (FOV 220 mm, TE 35ms, TR 2000 msec, flip angle of 79 degrees, 80 × 80 acquisition matrix interpolated to 128 × 128 image matrix, 28 slices, 3.5 mm thick with a skip of .35 mm. Similar parameters were used with adult participants; however, the four functional series had a FOV of 240 and a skip of .50 mm.

Data Analysis—All adult and child functional data were analyzed using Brainvoyager QX (Brain Innovations Inc). Each functional volume was motion corrected using 3D rigid body transformations to the first volume of the first functional run. All volumes that exceeded 3 mm or 3° of intra-session motion, in any direction, were removed both from the data set and design matrix. Each subject's fMRI data sets were adjusted for slice timing differences and spatially smoothed with a 6mm Gaussian kernel. Temporal drifts were removed with a linear trend removal. All individuals' functional data were coregistered to their own high-resolution 3D anatomic scan then normalized to Talairach standardized space [23]. A general linear model was fit at each voxel in each subject, including the data from all four runs, to produce parametric maps of normalized signal change for each task condition. Only positive activations were analyzed in the current study. A second-level analysis over all subjects was then used to generate a statistical t-map of the mean effect across each math task minus symbol-matching condition. Statistical maps were examined at two thresholds: uncorrected voxel-wise $p < 0.001$ and cluster volume $> 200 \text{ mm}^3$; and voxel-wise $p < 0.0001$. Talairach coordinates were derived from the local maxima of each cluster activated over the threshold. The Talairach Daemon [24] was used to identify the anatomical structures, considering those within 1 cm of the local maximum. Using the same parameters, we also performed adult and child comparisons for each math minus symbol-matching condition.

Results

Behavioral

Mean percentage correct and reaction times for adult and child performance on the in-magnet tasks are given in Table 1. Reaction times were calculated on correct answers only. Adults and children performed the tasks with high accuracy rates. Accuracy (percent correct) was similar between the two groups; a significant difference was found only on the single digit exact calculation task, where children were more accurate than adults (Mann-Whitney Independent test, $p < .001$). A significant difference in reaction time was found between the adult and child groups on all four tasks (Mann-Whitney Independent test, all tasks $p < .001$), favoring adults.

Functional MRI Results – Children

The regions identified as significantly activated from the group level statistical t-tests comparing each math task to its symbol-matching control task are shown in tables 2 and 3. The tables provide the Talairach coordinates, the cluster size, statistical maximum, and the Brodmann's Area (BA) for each cluster of activated voxels during the in-magnet tasks for the children. All regions identified during this analysis showed an increase in signal change during the experimental task compared to its symbol matching control. Figures 2 and 3 show the individual groups' brain activation patterns during the in-magnet tasks relative to their control tasks depicted on an inflated brain template. Regions of significant activation are listed here by task and discussed in more detail in the Discussion section.

Exact calculations—As shown in Table 2, children had significant activation in right hemisphere insula and medial frontal gyrus spreading bilaterally into the anterior cingulate during the single digit task. During the double digit task, their activation was distributed throughout the parietal, occipital and frontal lobes. The most intense activation during the double digit task was in a large cluster of activated voxels in the posterior superior parietal cortex. Local maxima within this larger cluster were identified in the right hemisphere precuneus, left hemisphere superior parietal lobe and the intraparietal sulcus.

Single digit and double digit exact calculation contrasts—To investigate the influence of complexity, we contrasted activation during the single digit exact calculation task to that of the double digit exact calculation task. During the single digit task, activation was more intense in the precentral, cingulate, medial frontal, and superior temporal gyri and the inferior parietal lobe (lateral). Increased activation in the double digit exact calculation version of the task was limited to the posterior parietal lobe including the precuneus, inferior parietal lobe (medial, near IPS), and angular gyrus.

Approximate calculations—During the single digit approximate calculation task, participants had bilateral activation in the parietal and frontal lobes. As shown in Table 3, parietal activations in the children were posterior in origin including the precuneus, angular gyrus, superior parietal lobe and inferior parietal lobe. Frontal lobe activation was bilateral in the medial gyrus and unilateral in the superior frontal and cingulate gyri.

Single digit and double digit approximate calculation contrasts—A direct comparison of the single digit to the double digit approximate calculation task revealed greater activation during the single digit task only. Activation differences were found in the right hemisphere occipital lobe and precuneus and in the left hemisphere precentral gyrus.

Across task comparisons—Direct comparisons were made between the exact and approximate calculation tasks at the same level of complexity. At the single digit level, increased activation during the exact calculation task was seen in the left hemisphere cingulate

gyrus and inferior parietal lobe and in the right hemisphere supramarginal gyrus. Increased activation during the single digit approximation task was seen bilaterally in the precuneus with a majority of the activation occurring in the right hemisphere. At the double digit level, activation was greater in the left hemisphere precuneus and fusiform gyrus during the approximation task.

Functional MRI Results - child and adult comparison

The direct contrasts between the children and the adults revealed significant group differences in prefrontal, cingulate, and parietal cortices during the calculation tasks. At our significance level, the majority of differences found were due to increased signal change in the adults. The results from this analysis are shown in tables 4 and 5. The tables give the Talairach coordinates, cluster size, statistical maximum, and Brodmann's Area (BA) for the cluster of voxels with increased signal change in the adults. Maps showing the adult to child contrasts are not included because inherent misregistration in the adult and child brain maps may exist. For this reason, we include as reference the adult activation maps during the single digit exact calculation and both double digit approximation tasks are provided in figures 4 and 5, respectively.

Exact Calculations—We found no areas of greater activation in the children compared with adults on the single or double digit exact calculation tasks. The adult to child contrast on the single digit exact calculation task revealed increased activation in adults' left hemisphere inferior parietal lobe and in the right hemisphere precuneus, fusiform gyrus, angular gyrus, and supramarginal gyrus. In the double digit exact calculation task, adults had greater bilateral activation in the precentral gyrus, and unilateral activation in the right hemisphere superior parietal lobe, middle frontal gyrus, and fusiform gyrus and in the left hemisphere inferior parietal lobe.

Approximate Calculations—On the single digit approximation task, a single region in the left hemisphere posterior cingulate cortex was found in which children had greater activation than adults (Tal coordinates $-1, -59, 24$). We found no areas of greater activation in children versus adults during the double digit approximate calculation tasks. For reference, figure 5 shows the activation patterns in adults during the single and double digit approximate calculation conditions. As shown in Table 5, adults exhibited significantly more bilateral activation than the children in the inferior frontal, precentral gyrus, middle frontal gyrus, superior frontal gyrus, and inferior parietal lobe during the single digit task. In addition, increased unilateral activation was found in adults' right hemisphere superior parietal lobe, superior temporal gyrus, precuneus and left hemisphere supramarginal gyrus. During the double digit approximation task, adults had greater bilateral activation in precuneus, posterior cingulate, and angular gyrus, precentral gyrus, middle frontal gyrus, middle temporal, fusiform gyrus, and lingual gyrus.

Discussion

The aims of the current study were to evaluate the neural correlates of exact and approximate processing systems in children and adults, and to investigate the influence of increased complexity on these systems. We found that despite activating similar regions to the adults during the exact calculation and approximation tasks, children, on average, had significantly weaker activations. These findings suggest that the number processing systems that support simple and complex exact and approximate calculation are in place by the third grade, but children do not recruit them at adult levels. Although these findings were analogous to those of previous imaging studies comparing children and adults, these data are a significant contribution to the field. The mixture of grade levels left unanswered the question of how grade level affected the results. A relative strength in the current study was that participants were all

in the same grade. Therefore, the overlap in the outcomes of our study with those of the other studies demonstrates that grade level differences did not have a significant influence on the results of the previous studies.

Consistent with previous imaging studies, children activated several regions in the posterior parietal cortex during the two types of calculation tasks. In particular, we observed activation in the inferior parietal lobe during all four in-magnet tasks. This early developing brain region is involved in the conceptualization of numerical magnitude [14-15,25-27]. Statistical contrasts between the single digit exact and approximate calculation tasks revealed task-related lateralization of parietal lobe activation in children that is similar to previous image study findings with adults: Activation was increased in left hemisphere during the exact calculation task and in the right hemisphere for the approximation task [25;28-29]. As a final point, with increasing arithmetic complexity, children had significantly increased activation in the angular gyrus and posterior parietal brain regions near the IPS [30]. All together, these findings contribute to the growing evidence in the field that the parietal systems for arithmetic reasoning are in place at a young age.

Children in the current study also engaged bilateral superior and medial frontal gyri (BA 8) and cingulate cortex (BA 24, 32) during the two types of calculation tasks. These brain regions are involved in attentional and working memory processes [31-32], and are active during calculation specific tasks as well as during non-mathematical tasks [33-34]. Recent studies have shown that during arithmetic tasks children compared to adults have increased activation in prefrontal regions. This activation likely reflects the use of compensatory strategies to perform the simple arithmetic tasks [14;17-18].

Related to this, children in the current study did not have left lateralized activation during the exact calculation task as expected. Adults retrieve arithmetic facts from long-term memory to solve simple addition problems [35-41]. Because adults store and retrieve simple arithmetic facts via their verbal representations (e.g. $2 + 2 = 4$ is stored as *two plus two equals four*), left hemisphere activation is frequently reported during exact calculation tasks [9]. During the beginning of third grade, however, children are still developing mental representations for arithmetic facts [27;37]. Our behavioral data showed that children and adults performed at comparable accuracy levels, but children had significantly slower response times. Slower response times in children compared to adults is consistent with behavioral research demonstrating that memory retrieval strategies develop through adolescence, causing an increase in response time speed with age [42-43]. For these reasons, we propose that the absence of left hemisphere activation in our participants reflected the use of a nonverbal strategy to solve the simple exact calculation problems. Unfortunately, we did not gather behavioral data on strategy use; however, children's activation in the right hemisphere insula (BA 13) may provide valuable insight into the type of strategy that they did use. The location of activation is in close proximity to brain regions associated with orientation of spatial attention [44] and visuospatial processing [45]. Therefore, the insula activation may signify that children engaged visuospatial resources to perform the task [46-47]. Alternatively, it is also possible that activation in this region was associated with induced emotion and anxiety level from the research environment [48]. Future studies would benefit from the administration of a strategy use assessment to explore the relationship between strategy use and functional activations.

Children's activations during all four tasks occurred in virtually identical locations as the adults, suggesting that the neural circuitry underlying the cognitive processes for arithmetic is in place by third grade. On the other hand, three anatomical regions were identified in which adults activations were greater than children's activations. First, adults had increased activation in posterior parietal brain regions that are critical to arithmetic processing (BA 7, 40, 39). In particular, adults' had greater activation in the left hemisphere IPS during the exact calculation

tasks and in the right hemisphere posterior parietal lobe during the approximation tasks. These findings support the theory proposed by Rivera et al. [18] and Ansari et al. [14] that the parietal lobes become specialized for calculation with experience. Second, adults had increased activation in the dorsolateral prefrontal cortex (DLPFC, BA 9). The DLPFC is associated with increased executive functioning and working memory [49-51], activates during calculation as well as during non-mathematical tasks [33-34], and may play a critical role in the suppression of distracting information from entering working memory [52-53]. Third, adults had increased activation in the occipital-temporal (BA 37) and extrastriate regions (BA 18, 19), which are important for symbol recognition [54-58]. Increased activation in these regions was a result of adults' greater experience with written numbers. Adults' increased activation in these three brain regions is evidence that the neural circuitry underlying the cognitive processes for arithmetic may be in position by third grade, but it is still under development.

A noteworthy finding in the current study was a brain region that had a positive task-related signal change in children and a negative task-related signal change in adults during the single digit approximation task. This centrally located region spread across both hemispheres from the posterior occipital cortex to the posterior cingulate (Talairach Coords: -3, -61, 19). A similar finding was reported in Kucian et al. [17]. The region is structurally interesting because it has extensive connections with prefrontal and other parietal regions [59]. In addition, the posterior cingulate appears to be part of the early developing default mode network [60]. The default mode network is a group of brain regions that have negative activation during a broad range of cognitive tasks [61]. However, significant development occurs in the default mode network throughout childhood [62]. Therefore, this finding may be related to neurodevelopmental differences between adults and children that are not specific to the mathematical task (Kucian et al., 2008). Regardless, the replication of the Kucian et al. finding in the current study stresses the importance of future studies measuring the default mode network in children.

In conclusion, we propose that our findings corroborate previous reports that the neural pathways for exact and approximate calculation appear to be in place at a young age, but are still developing. Differences between our study and previous studies with children are likely due to the fact that the present study is a snapshot of the diverse brain regions involved in simple mathematical processes during the third grade, which is a time of huge developmental growth in mathematical skill. Granted, several additional variables could account for the group differences in functional activation. For example, developmentally based anatomical differences could potentially explain the group differences in activation level [63-64]. Yet, anatomical differences between adults and children are expected to be only a minor confound [65]. Differences would also occur if the children failed to perform the tasks while they were in the magnet. In the present study, we are confident this did not occur because the two groups had comparable accuracy scores on the in-magnet tasks.

Limitations

This study has two limitations. First, differences in the way adults and children approach the tasks could explain our results. Children may add the problem first and then compare the response to the available answers rather than solve the problem as a true approximation. It is also possible that adults saw the task as a game and attempted to answer as many questions as possible within the timed block, in a sense trading accuracy for speed. This would not affect the interpretation of the task, because the adults still performed the task as instructed. It is also tenable that adults were bored with the simplicity of the task, and they carelessly answered the simple, single digit exact calculation task. If so, interpretation of results for this task would be affected. Second, some of our results may be due to maturation differences in white matter development that occurs throughout childhood and adolescence [66-67]. For these reasons,

future studies would be improved by adding self-report data on strategy use and gathering data on white matter pathways with diffusion tensor imaging.

Acknowledgements

This work was supported in part by the National Institutes of Health through the NIH Roadmap for Medical Research T32 MH75883, the National Institute of Child Health and Development/Department of Education HD046261, the National Institutes of Mental Health through the NIH Roadmap for Medical Research T32 MH075883, and by the National Institute of Child Health and Development/Department of Education HD046261. We would like to thank Jack Fletcher and Whitney Schrader for their assistance during the course of this project.

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Figure 1.

Task paradigm for fMRI included five tasks: single digit exact calculation, single digit approximate calculation, double digit exact calculation, double digit approximate calculation, and control. For all tasks, the equation was presented without the answer for 1000 msec and then the equation with answer choices appeared on the screen until the participant responded.

Figure 2.

Brain activation patterns of children during the exact calculation tasks are depicted on an inflated brain template. The top rows show the lateral cortex and the bottom rows show the medial cortex. A) Activations revealed by single digit exact calculation minus a control task, uncorrected p at .001, B) Activations revealed by double digit exact calculation minus a control task, uncorrected p at .001. The colored key provides significance levels for activation at each of the significance levels.

Figure 3.

Brain activation patterns of children during the approximate calculation tasks are depicted on an inflated brain template. The top rows show the lateral cortex and the bottom rows show the medial cortex. A) Activations revealed by single digit approximate calculation minus a control task, uncorrected p at .001, B) Activations revealed by double digit approximate calculation task minus a control task, uncorrected p at .001. The colored key provides significance levels for activation.

Figure 4.

Brain activation patterns of adults during the double digit exact calculation tasks are depicted on an inflated brain template. The top rows show the lateral cortex and the bottom rows show the medial cortex. Activations revealed by double digit exact calculation minus a control task, uncorrected p at .001. The colored key provides significance levels for activation at each of the significance levels.

Figure 5.

Brain activation patterns of adults during the approximate calculation tasks are depicted on an inflated brain template. The top rows show the lateral cortex and the bottom rows show the medial cortex. A) Activations revealed by single digit approximate calculation minus a control task, uncorrected p at .001, B) Activations revealed by double approximate exact calculation minus a control task, uncorrected p at .001. The colored key provides significance levels for activation at each of the significance levels.

Table 1

Descriptive Statistics In-Magnet Tasks

Task	% Correct	Reaction time (ms)
<i>Children</i>		
single digit exact calculation	97 (5.9)	2080 (1447)
double digit exact calculation	88 (13.9)	5671 (2488)
single digit approximation	88 (7.7)	2825 (982)
double digit approximation	79 (13.7)	5837 (2233)
<i>Adults</i>		
single digit exact calculation	94 (1.3)	677 (324.6)
double digit exact calculation	88 (6.1)	1590 (849)
single digit approximation	89 (3.7)	1355 (373)
double digit approximation	83 (6.5)	2082 (1466)

Mean accuracy and response time of in-magnet tasks with standard deviations in parentheses.

Table 2
Location, Size, and Magnitude of Children's Activations on the Exact Calculation Tasks Compared to the Control Task

Task	Anatomical Region	Talairach coordinates			cluster size	Stat Max (T)	BA
		X	Y	Z			
Single Digit Exact Calculation ($p < .001$, uncorrected; $p = .05$, FDR corrected at T of 4.13)							
	right claustrum	33	14	7	495	5.84	-
	<i>right insula</i>	30	23	13		4.73	13
	right medial frontal gyrus	3	20	43	1315	5.07	8
	<i>right cingulate gyrus</i>	6	8	40		4.62	32
	<i>left cingulate gyrus</i>	-9	11	37		4.33	32
Double Digit Exact Calculation ($p < .001$, uncorrected; $p = .01$, FDR corrected at T of 4.05)							
	left precuneus*	-21	-79	40	13083	7.57	19
	<i>right cuneus</i>	3	-82	31		5.57	19
	<i>left superior parietal lobe</i>	-9	-70	55		5.16	7
	<i>left inferior parietal lobe</i>	-30	-52	37		4.85	40
	<i>right precuneus</i>	12	-64	40		4.55	7
	left superior frontal gyrus*	0	14	49	1857	6.12	6
	<i>left cingulate gyrus</i>	-3	20	40		5.67	32
	left medial frontal gyrus	-18	2	49	619	5.82	6
	right middle frontal gyrus	24	-1	49	234	5.47	6
	right lingual gyrus*	6	-91	1	1782	5.43	17
	<i>right cuneus</i>	6	-94	10		4.70	18
	left inferior occipital gyrus	-15	-91	-11	300	4.89	17
	left lingual gyrus	-3	-73	1	396	4.20	18

cluster size in voxels; italicized regions are local maxima within the larger cluster of activation.

* region remains at $p < .0001$

Table 3
Location, Size, and Magnitude of Children's Activations on the Approximate Calculation Tasks Compared to the Control Task

Task	Anatomical Region	Talairach coordinates			cluster size	Stat Max (T)	BA
		X	Y	Z			
Single Digit Approximation ($p < .001$, uncorrected; $p = .01$, FDR corrected at T of 4.16)							
	left precuneus*	-3	-64	43	8780	7.60	7
	<i>right precuneus</i>	6	-73	49		6.80	7
	<i>right superior parietal lobe</i>	27	-70	43		5.79	7
	left superior frontal gyrus*	0	17	49	2754	6.56	8
	<i>left medial frontal gyrus</i>	-6	26	40		5.29	8
	<i>right medial frontal gyrus</i>	3	32	40		5.09	8
	left middle frontal gyrus	-21	2	52	353	5.46	6
	left cuneus	-24	-82	28	2284	5.25	19
	<i>left angular gyrus</i>	-30	-55	37		5.13	39
	<i>left precuneus</i>	-24	-73	34		4.53	19
	<i>left inferior parietal lobe</i>	-36	-52	46		3.83	40
	right precuneus	24	-79	46	229	5.21	7
	<i>right superior parietal lobe</i>	30	-73	49		4.84	7
	right middle frontal gyrus	24	5	52	428	5.08	6
	<i>right cingulate gyrus</i>	21	5	40		4.65	24
	left precuneus	-21	-76	46	404	4.83	7
	left middle temporal	30	-70	28	296	5.32	-
	<i>right angular gyrus</i>	30	-64	34		4.18	39
Double Digit Approximation ($p < .001$, uncorrected; $p = .01$, FDR corrected at T of 4.02)							
	left superior frontal gyrus*	0	14	49	3404	6.09	6
	<i>right medial frontal gyrus</i>	3	20	43		5.22	8
	<i>left cingulate gyrus</i>	-3	26	37		4.93	32
	left precuneus*	-30	-64	37	2237	5.94	19
	<i>left superior parietal lobe</i>	-27	-73	43		4.63	7
	<i>left inferior parietal lobe</i>	-33	-55	40		4.24	40
	right inferior parietal lobe	39	-43	40	473	4.96	40
	left precentral gyrus	-42	-1	28	357	4.41	6

cluster size in voxels; italicized regions are local maxima within the larger cluster of activation.

* region remains at $p < .0001$

Table 4

Location, Size, and Magnitude of Adult's Activations compared to Children's Activations on the Exact Calculation Tasks Compared to the Control Task

Task	Anatomical Region	X	Y	Z	cluster size	Stat Max (T)	BA
Single Digit Exact Calculation ($p < .001$, uncorrected)							
	right supramarginal gyrus	48	-40	31	274	4.59	40
	right fusiform	42	-55	-14	597	4.49	37
	<i>right middle temporal gyrus</i>	42	-61	-2		3.72	37
	right occipital-temporal lobe	33	-58	28	2237	4.31	39
	<i>right angular gyrus*</i>	43	-58	37		4.21	39
	<i>right superior parietal lobe</i>	30	-55	43		4.15	7
	<i>right precuneus</i>	27	-67	40		4.14	7
	left inferior parietal lobe	-43	-52	49	486	4.11	40
	<i>left superior parietal lobe</i>	-36	-56	52		3.68	7
Double Digit Exact Calculation ($p < .001$, uncorrected; $p = .05$, FDR corrected at T of 3.54)							
	right precentral gyrus*	39	2	31	3787	7.36	6
	<i>right medial frontal gyrus</i>	24	-1	31		4.12	-
	right superior parietal lobe*	30	-52	40	1801	5.59	7
	<i>right precuneus</i>	27	-58	31		3.98	7
	left inferior parietal lobe*	-42	-43	40	1446	5.37	40
	left precentral gyrus*	-42	5	34	2102	5.32	9
	right middle frontal gyrus	30	32	34	323	4.78	9
	right fusiform gyrus	36	-67	-11	208	4.12	19
	left precentral gyrus	-30	-16	59	332	3.73	6

cluster size in voxels; italicized regions are local maxima within the larger cluster of activation.

* region remains at $p < .0001$

Table 5

Location, Size, and Magnitude of Adult's Activations versus Children's Activations on the Approximate Calculation Tasks Compared to the Control

Task	Anatomical Region	Talairach coordinates			cluster size	Stat Max (T)	BA
		X	Y	Z			
Single Digit Approximation ($p < .001$, uncorrected; $p = .05$, FDR corrected at T of 3.43)							
	right inferior frontal gyrus*	36	5	28	5286	6.06	9
	<i>right middle frontal gyrus</i>	27	-7	52		5.72	6
	<i>right precentral gyrus</i>	39	-1	40		4.71	6
	right inferior parietal lobe*	42	-34	37	2134	5.58	40
	<i>right postcentral gyrus</i>	52	-28	40		3.99	2
	left inferior frontal gyrus*	-39	5	31	1881	5.34	9
	<i>left precentral gyrus</i>	-30	8	31		5.10	6
	<i>left middle frontal gyrus</i>	-45	5	40		4.32	6
	right angular gyrus*	30	-58	31	4824	5.28	39
	<i>right superior parietal lobe</i>	27	-70	47		5.26	7
	<i>right superior occipital lobe</i>	30	-70	28		4.08	-
	<i>right precuneus</i>	27	-46	49		4.01	7
	right superior frontal gyrus*	3	11	49	799	4.94	6
	right precuneus	12	-67	46	361	4.00	7
	left middle frontal gyrus	-30	47	25		4.31	10
	<i>left superior frontal gyrus</i>	-24	47	31		4.22	9
	left supramarginal gyrus	-45	-43	34	475	3.85	40
	<i>left inferior parietal lobe</i>	-39	-52	53		3.67	40
Double Digit Approximation ($p < .001$, uncorrected; $p = .05$, FDR corrected at T of 3.04)							
	right inferior frontal gyrus*	39	8	31	6481	7.56	9
	<i>right precentral gyrus</i>	42	-1	40		5.16	6
	<i>right superior frontal gyrus</i>	27	51	28		5.13	9
	<i>right middle frontal gyrus</i>	27	-7	59		4.40	6
	right precuneus*	27	-61	34	10650	6.28	7
	<i>right inferior parietal lobe</i>	39	-34	37		5.57	40
	<i>right angular gyrus</i>	33	-55	37		5.47	39

Task	Anatomical Region	Talairach coordinates			cluster size	Stat Max (T)	BA
		X	Y	Z			
	<i>right superior parietal lobe</i>	33	-67	47		4.83	7
	<i>right supramarginal gyrus</i>	39	-43	34		4.50	40
	<i>right postcentral gyrus</i>	48	-28	40		4.19	2
	left precentral gyrus*	-42	-1	40	13037	6.27	6
	<i>left inferior parietal lobe</i>	-42	-43	40		5.67	40
	<i>left supramarginal gyrus</i>	-42	-37	34		4.72	40
	<i>left superior parietal lobe</i>	-27	-49	43		4.53	7
	<i>left middle frontal gyrus</i>	-24	-7	59		4.50	6
	<i>left precuneus</i>	-15	-70	43		4.47	7
	<i>left postcentral gyrus</i>	-45	-28	37		4.43	2
	<i>left middle temporal gyrus</i>	-27	-61	28		4.27	39
	right medial frontal gyrus*	3	11	46	981	5.66	6
	right fusiform gyrus*	42	-55	-8	1822	4.74	37
	<i>right lingual gyrus</i>	27	-70	-8		4.73	18
	left inferior temporal gyrus	-48	-67	1	2337	4.05	37
	<i>left inferior occipital gyrus</i>	-39	-77	-5		3.98	19
	<i>left lingual gyrus</i>	-27	-73	-8		3.71	18

cluster size in voxels; italicized regions are local maxima within the larger cluster of activation.

* region remains at $p < .0001$