The Neural Development of an Abstract Concept of Number

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Abstract

■ As literate adults, we appreciate numerical values as abstract entities that can be represented by a numeral, a word, a number of lines on a scorecard, or a sequence of chimes from a clock. This abstract, notation-independent appreciation of numbers develops gradually over the first several years of life. Here, using functional magnetic resonance imaging, we examine the brain mechanisms that 6- and 7-year-old children and adults recruit to solve numerical comparisons across different notation systems. The data reveal that when young children compare numerical values in symbolic and nonsymbolic notations, they invoke the same network of brain regions as adults including occipito-temporal and parietal cortex. However, children also recruit inferior frontal cortex during these numerical tasks to a much greater degree than adults. Our data lend additional support to an emerging consensus from adult neuroimaging, nonhuman primate neurophysiology, and computational modeling studies that a core neural system integrates notation-independent numerical representations throughout development but, early in development, higher-order brain mechanisms mediate this process. ■

INTRODUCTION

In the course of formal schooling, children pass through a series of challenging developmental milestones in mathematical competence: they learn to add and subtract, they learn to multiply and divide, they learn fractions, and eventually, they might learn calculus. However, before all of these learning can occur, children must deeply understand the meaning of numbers. Thus, a principle question in the study of mathematical cognition is: What changes take place in the brain and cognition as children master the meaning of numbers? In the cognitive domain, considerable progress has been made toward mapping the development of children's numerical understanding.

Several studies have identified early developing numerical concepts in human infants (e.g., Xu, Spelke, & Goddard, 2005; McCrink & Wynn, 2004; Lipton & Spelke, 2003; Brannon, 2002; Xu & Spelke, 2000; Wynn, 1992; see Feigenson et al., 2004 for a review). By at least 9 months, infants understand that when one set of objects is combined with another set of objects, the resulting number of objects corresponds to the sum of the two sets (McCrink & Wynn, 2004). Thus, human infants appreciate numerical quantities at a nonsymbolic level: They know approximately how many objects they see before them even though they do not understand number words or Arabic numerals. These fundamental, nonverbal numerical concepts persist into childhood and even adulthood. For example, adults and preschool children can rapidly identify which of two sets contains a larger number of objects without verbally counting the objects in each set (e.g., Barth, La Mont, Lipton, & Spelke, 2005). The implication is that a nonverbal system of numerical representation, originating in infancy, continues to function throughout childhood and into adulthood for the rapid assessment of nonsymbolic numerical quantities.

One psychological principle of nonsymbolic numerical judgments is that an individual's ability to rapidly discriminate numerical values hinges on both the overall *magnitude* and numerical *distance* between the values to be discriminated. For example, children and adults are faster and more accurate at choosing the larger of 4 versus 6 than 8 versus 10 because, with an equal distance between values, larger numbers are more difficult to discriminate than smaller values. In terms of distance, numbers that are farther apart are easier to discriminate than values that are close together (e.g., 3 vs. 9 is easier than 3 vs. 6). The combined impact of magnitude and distance effects on numerical judgments results in performance that is modulated by the ratio between numerical values (Weber's law).

There is considerable evidence that numerical ratio modulates performance on nonsymbolic numerical tasks for adults (e.g., Cantlon & Brannon, 2006, 2007; Barth, Kanwisher, & Spelke, 2003; Cordes, Gelman, Gallistel, &

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Whalen, 2001; Whalen, Gallistel, & Gelman, 1999; Buckley & Gillman, 1974) and children (Cantlon & Brannon, submitted; Cantlon, Fink, Safford, & Brannon, 2007; Barth et al., 2005; Brannon & van de Walle, 2001; Huntley-Fenner, 2001; Huntley-Fenner & Cannon, 2000; Temple & Posner, 1998; Gallistel & Gelman, 1992). The numerical ratio effect manifests during both symbolic numerical comparisons of Arabic numerals and number words in both adults and children (e.g., Gilmore, McCarthy, & Spelke, 2007; Huntley-Fenner & Cannon, 2000; Temple & Posner, 1998; Dehaene, Dupoux, & Mehler, 1990; Moyer & Landaeur, 1967; see Dehaene, 1992 for a review). Thus, the numerical ratio effect applies to numerical judgments across notation systems.

The notation-independent numerical ratio effect in humans' numerical performance is evidence that there is a unitary system for representing and/or comparing symbolic and nonsymbolic numerical values. In fact, recent behavioral studies have made a compelling case that the nonsymbolic system forms the semantic basis of symbolic numerical operations over development (Gilmore et al., 2007; Lipton & Spelke, 2005). The implication here is that these two modes of numerical representation may emerge from a common cognitive source in children.

Neuropsychological, neuroimaging, and neurophysiological studies of numerical judgments in adults and nonhuman primates have honed in on parietal cortex as a locus important for semantic processing of numbers (see Dehaene, Piazza, Pinel, & Cohen, 2003; Butterworth, 1999; Dehaene, 1997 for reviews). A common finding among these studies is that the neural response in parietal cortex is selective for numerical value over other stimulus dimensions (e.g., Castelli, Glaser, & Butterworth, 2006; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Naccache & Dehaene, 2001; Dehaene & Cohen, 1997). In addition, the discrimination of numerical representations in parietal cortex, at the neural level, is ratio-dependent (Nieder, Diester, & Tudusciuc, 2006; Nieder & Miller, 2004; Piazza et al., 2004; Pinel et al., 2004; Pinel, Dehaene, Riviere, & Lebihan, 2001).

In terms of BOLD activity, the numerical ratio effect manifests in increased BOLD activity to numerical values at fine numerical ratios relative to values at crude numerical ratios. For example, in an fMRI adaptation study by Piazza et al. (2004), the BOLD response to the numerical value 12 after adaptation to the numerical value 32 was weaker than the BOLD response to 12 after adaptation to the value 16. This is because the ratio of 12:16 (0.75) is finer, or more difficult to discriminate, than the ratio of 12:32 (0.375). Two recent studies have demonstrated that, in adults, this numerical ratio effect in BOLD activity in parietal cortex holds for numerical values presented in various numerical notations including Arabic numerals, number words, and arrays of dots (Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007; Piazza, Pinel, Le Bihan, & Dehaene, 2007; see also Libertus, Woldorff, & Brannon, 2007). All of these studies have identified a numerical ratio effect in BOLD activity during passive viewing of numerical stimuli without an explicit behavioral task.

What is currently known about the early stages of numerical processing in the brain is that by at least 4 years of age, children exhibit a number-selective response in parietal cortex to numerical values expressed nonsymbolically as visual arrays of elements (Cantlon, Brannon, Carter, & Pelphrey, 2006). A recent ERP study of human infants suggests that nonsymbolic number-related activity may emerge in parietal cortex much earlier in development (Izard, Dehaene-Lambertz, & Dehaene, 2008). Furthermore, alpha-band oscillations over posterior brain regions show ratio-dependent modulation during numerical processing in 7-month-old infants (Libertus, Pruitt, Woldorff, & Brannon, submitted). Infants at this age also exhibit adult-like patterns of EEG activity when detecting erroneous outcomes from simple nonverbal arithmetic displays (Berger, Tzur, & Posner, 2006).

By 5 years of age, the majority of children are capable of ordering Arabic numerals, at least for values less than 10. One ERP study reported that at this age, electrodes over parietal cortex detect activity that is modulated by the difference between numerical values for Arabic numerals and arrays of dots representing values 1 through 9 (Temple & Posner, 1998). However, in this prior study, there were qualitative and quantitative differences in the ERP waveforms between the 5-year-old children and adult subjects and the relationship between these neural differences and numerical performance was not clear (see Libertus et al., 2007 for a possible explanation of these differences). Furthermore, scalp-level ERP differences are difficult to relate to precise brain systems. Thus, in terms of development, the neural sources of abstract, semantic knowledge of numbers are largely unknown.

With the exception of the studies described above, most of what is known about the development of numerical cognition in the brain comes from studies of children older than 9 years and teenagers (e.g., Ansari & Dhital, 2006; Kaufmann et al., 2006; Kucian et al., 2006; Ansari, Garcia, Lucas, Harmon, & Dhital, 2005; Rivera, Reiss, Eckert, & Menon, 2005; see Ansari, 2008 for a review). Additionally, developmental neuroimaging studies have predominantly focused on only a single numerical notation system (*Arabic numerals*: Kaufmann et al., 2006; Ansari et al., 2005; Rivera et al., 2005; *arrays of dots*: Ansari & Dhital, 2006; Cantlon et al., 2006). Collectively, these prior studies have provided important evidence of a common network of frontal and parietal regions that subserves numerical operations in older children and adults. However, data that address the neural development of abstract numerical concepts in young children are sparse. Furthermore, there are few data on the relationship between individual variability in abstract numerical knowledge and brain activity in young children. Such data are critical for understanding the connection between behavioral and brain development in the numerical domain.

In the current study, we recorded brain activity with fMRI while 6- to 7-year-old children (n = 14) and adults (n = 14) performed a number comparison task. Subjects were presented with two numerical stimuli simultaneously on a computer monitor and pressed a button corresponding to the side of the screen hosting the larger numerical value (Figure 1). Half of the trials required subjects to make judgments about Arabic numerals (symbolic), whereas the remaining half of trials required subjects to judge the numerical value of arrays of dots (nonsymbolic). Numerical values ranged from 2 to 56 and were presented in one of two numerical ratios: 0.5 (easy) or 0.8 (difficult). We conducted fMRI scans as subjects performed this task to measure the brain response to numerical judgments across notation systems in children and adults. We then compared patterns of brain activity between children and adults during judgments of the symbolic and nonsymbolic numerical stimuli to identify developmental differences in the brain regions recruited to solve numerical problems independent of notation. Finally, we examined the relative variability in brain activity and behavior in children to explore the neural sources of individual differences in numerical performance.

METHODS

Using fMRI, we compared the brain activity of adults and 6- to 7-year-old children as they performed symbolic and nonsymbolic numerical comparisons. Children and adults were presented with two numerical values, simultaneously, and their task was to select the larger of the two values. During symbolic numerical comparisons, adults and children were presented with two Arabic numerals, whereas during nonsymbolic numerical comparisons, they were tested with two arrays of dots (Figure 1). All participants were instructed to respond as quickly as possible and were only allowed 2 sec to respond during each trial to prevent them from verbally counting during the nonsymbolic condition. The same numerical comparisons were tested in symbolic and nonsymbolic conditions and were either in a 0.5 ratio (e.g., 2 vs. 4, 28 vs. 56) or a 0.8 ratio (e.g., 6 vs. 8, 21 vs. 28). By including numerical comparisons of two different numerical ratios, we could investigate the presence of a numerical ratio effect in the activity of brain regions that respond during symbolic and nonsymbolic numerical comparisons.

Participants

Fourteen healthy adults (6 women; mean age = 24 years, SD = 3.05) and 14 typically developing 6- to 7-year-old children (7 girls; mean age = 7.2 years, SD = .58) consented to participate in this study. Originally, 20 children participated in this study. However, four children were excluded due to excessive motion (i.e., >5 mm) and two children were excluded due to scanner errors that rendered their data unusable.

During the functional scan sequence, the included child participants moved, on average, 1 mm more than adult participants. The overall amount of motion in the x-, y-, and z-axes, calculated from the center of mass index for each subject over each scanning run, did not significantly differ between the child and adult participants [$t(26) = 1.97$, $p = .06$, child mean = 3 mm, adult mean = 2.1 mm). Within this overall comparison, children and adults did not significantly differ in the amount of motion along the x- and y-axes (x = 1.3 vs. 1.2 mm and y = 4.3 vs. 3.5 mm, both ps > .26), but they differed reliably by 1.5 mm along the z-axis [3.3 vs. 1.8 mm, $t(26)$ = 2.34, $p < .05$]. Direct statistical contrasts between children and adults should be considered cautiously, with these motion differences in mind. However, it also should be noted that motion correction algorithms were

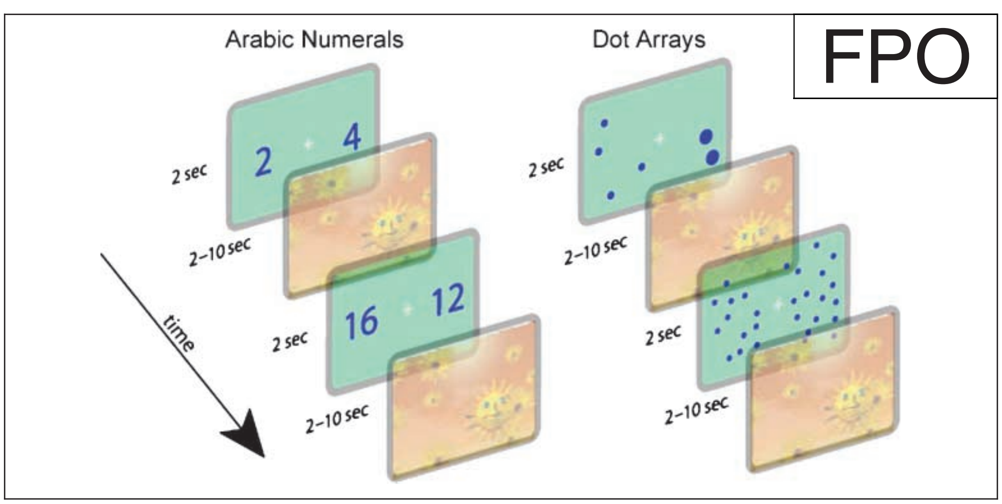

Figure 1. The task design. During half of all trial blocks, children and adults chose the larger of two Arabic numerals, whereas the other half of trials required subjects to choose the larger number from two arrays of dots. Participants responded by pressing a button corresponding to the side of the screen with the correct answer. Each trial was presented for 2 sec with 2 to 8 sec between trials. Subjects were presented with a picture of a sun following correct responses.

applied to all data, and motion parameters were included as regressors in the functional data analysis.

Stimuli, Task, and Procedure

Prior to the actual scanning session, children were given a half-hour training session in a mock scanner to familiarize them with the scanner environment, experimental task, and to prepare them to remain motionless throughout the scan. Immediately following the training session, children were tested in the actual MR scanner. In the actual scanner, medical tape (turned sticky-side out) and foam padding were used to secure children's head position. Adults did not receive a mock-scanner training session prior to the experimental session but received verbal instructions and a brief task practice session prior to the actual MR scanning session.

During the experimental session, subjects were tested over four 6-min runs (2 runs with Arabic numerals and 2 runs with arrays of dots). Each run consisted of approximately 72 trials for an average total of 288 trials per subject. Half of the trials in each run were numerical comparisons in a 0.5 ratio (2 vs. 4, 4 vs. 8, 8 vs. 16, 12 vs. 24, and 28 vs. 56) and the remaining half were comparisons in a 0.8 ratio (3 vs. 4, 6 vs. 8, 9 vs. 12, 16 vs. 21, and 21 vs. 28). The same numerical comparisons were tested in symbolic (Arabic numeral) and nonsymbolic (dot array) notations. Stimuli were presented in pairs, one on each side of a fixation cross, and subjects had to decide which of the two stimuli contained the larger number. Each stimulus was equally likely to appear on the left or right side of the fixation cross. Subjects responded by pressing the button that corresponded to the side of the screen with the larger number. All subjects responded with their right hand, first two fingers.

On each trial, subjects had a temporal window of 2 sec in which to respond. After 2 sec, the stimuli disappeared and a black screen was presented for 2 to 8 sec. Stimuli were presented on the screen for a minimum of 1 sec and a maximum of 2 sec. Within this window, stimuli disappeared when subjects made a response. When subjects correctly selected the larger of the two numerical values, they were presented with a picture of a sun for a random period of time between 2 and 8 sec, but when they responded incorrectly, they were presented with a black screen for a random period of time between 2 and 8 sec. During the poststimulus feedback period, subjects fixated a central crosshair. The purpose of the feedback was to motivate children to continue responding and to respond correctly during the task. All task responses recorded during the scan were included in our behavioral analyses.

Arabic numerals were presented in 300-point font. Dot arrays consisted of circles that varied in size, element position, and density to ensure that subjects attended to the number of elements rather than element size, density, or cumulative surface area. Approximately half of all trials within each ratio presented the larger numerical value with the greater cumulative surface area, whereas on the remaining half of trials, the smaller numerical value was greater along this dimension. Thus, if subjects were using cumulative surface area in lieu of number to select the correct stimulus, their performance should be at chance.

For dot arrays, the cumulative surface area value for each numerical value in a pair was randomly selected from a single distribution consisting of the values (in pixel units from a 1024 $\times$ 768 screen resolution) 2356, 3534, 4712, 7068, and 9424. Furthermore, the ranges of element sizes for the smaller and larger numbers in each pair overlapped considerably (smaller: 84 to 4712; larger: 42 to 2356). Finally, the average density of the elements for the smaller and larger number in each pair was approximately equal (smaller: 0.00019; larger: 0.00028).

Image Acquisition Parameters

Image data were acquired on a 3-Tesla General Electric Signa Excite scanner. An echo-planar imaging pulse sequence was employed to detect BOLD T2* contrast (TR = 2000 msec, TE = 27 msec, flip angle = 60°, FOV = 25.6 cm, matrix = 64 $\times$ 64, slice thickness = 4 mm). There were four functional runs per session and 180 volumes were collected in each run. High-resolution structural T1 contrast images were acquired at the beginning of each session (TR = 22 msec, TE = 5.4 msec, flip angle = 12°, FOV = 25.6 cm, matrix = 256 $\times$ 256, slice thickness = 2 mm).

Image Processing and Analysis

Images were processed and analyzed in SPM2 (www.fil.ion.ucl.ac.uk/spm). All volumes were (1) corrected for slice acquisition timing, (2) spatially aligned to the first volume of the session, (3) spatially smoothed to 8 mm, and (4) normalized to the Montreal Neurological Institute standard template at a resolution of 2 $\times$ 2 $\times$ 2 mm. The linear model applied to the images included the SPM2 standard hemodynamic response function convolved with trial onsets, separately for each stimulus notation; a modulator parameter within each notation, whereby numerical ratio on each trial, mean-centered to zero, was multiplied with the trial-specific hemodynamic response function; a temporal derivative parameter; and six motion parameters. Image analyses were random effects statistics conducted between conditions (Arabic numerals or Dot Arrays) versus an implicit baseline and, to test for the effect of numerical ratio, we conducted a statistical contrast with a positive weight for the modulator parameter of ratio.

For children and adults, the initial contrasts of Arabic numerals versus baseline and dot arrays versus baseline were conducted at a statistical threshold of $p < .05$, cluster size $\geq$ 8 voxels and the results of these contrasts were submitted to a second random effects test for the conjunction of Arabic numerals and Dot Arrays analyses, resulting in an overall statistical threshold of $p < .003$ (uncorrected, cluster size $\geq$ 8 voxels). The results of this analysis were then submitted to a two-sample t test for a between-groups comparison of children versus adults. Finally, the statistical analysis of ratio modulation was conducted within the results of the conjunction analysis.

RESULTS

Behavioral Results

Children and adults performed significantly above chance on both the Arabic numerals and dot arrays comparisons (one-sample t tests vs. chance = 50%, all ps $< .05$). An ANOVA with factors of Group (children, adults) × Notation (Arabic, dots) × Ratio (0.5, 0.8) with a repeated measure of accuracy revealed main effects of group [$F(1, 52) = 35.3, p < .001$], notation [$F(1, 52) = 9.28, p < .005$], and ratio [$F(1, 52) = 92.24, p < .001$]. These main effects reflect the facts that: (1) adults performed more accurately than children (93% vs. 80%); (2) performance on Arabic numerals was higher than on dot arrays (90% vs. 83%); and (3) performance on the easy 0.5 numerical ratio was better than on the difficult 0.8 numerical ratio (91% vs. 82%). The only significant interaction was between notation and ratio, owing to a greater effect of ratio in the dot arrays condition than in the Arabic numerals condition (dot arrays ratio effect = 15%; Arabic numerals ratio effect = 3%).

An ANOVA with factors of Group (children, adults) × Notation (Arabic, dots) × Ratio (0.5, 0.8) with a repeated measure of response time revealed main effects of group [$F(1, 52) = 74.8, p < .001$], notation [$F(1, 52) = 9.01, p < .001$], and ratio [$F(1, 52) = 38.14, p < .001$]. Adults performed significantly faster than children (1041 vs. 723 msec), performance on Arabic numerals was faster than on dot arrays (938 vs. 827 msec), and performance on the easy 0.5 numerical ratio was faster than on the difficult 0.8 numerical ratio (851 vs. 913 msec). In addition, there was an interaction between notation and ratio with a greater effect of ratio in the dot arrays condition than in the Arabic numerals condition (dot arrays ratio effect = 112 msec; Arabic numerals ratio effect = 13 msec). No other interactions were significant.

fMRI Results

The strongest test of a numerical, notation-independent brain response requires that brain regions (1) evoke a positive response to numerical values independent of notation and (2) exhibit activity that is modulated by numerical ratio. Therefore, our analysis strategy was to (1) identify regions that exhibit a significant BOLD response during judgments of *both* Arabic numerals and dot arrays and then (2) test these regions for the presence of a numerical ratio effect. In a final set of analyses, we examine the BOLD activity as a function of children's behavioral performance on each of the two numerical tasks.

We performed a random effects analysis separately for children and adults over individual conjunction maps of regions that generated a significant response to both the Arabic numeral and dot array conditions. Regions that exhibited a significant response during numerical judgments of both Arabic numerals and dot arrays are shown in Figure 2. To illustrate the common regions of activation between children and adults, the results of this analysis are plotted in the same image space for both groups. Table 1 reports the coordinates of the peak voxels from regions exhibiting a significant conjunction between Arabic numerals and dot arrays for children and adults. Regions that exhibited a significant increase

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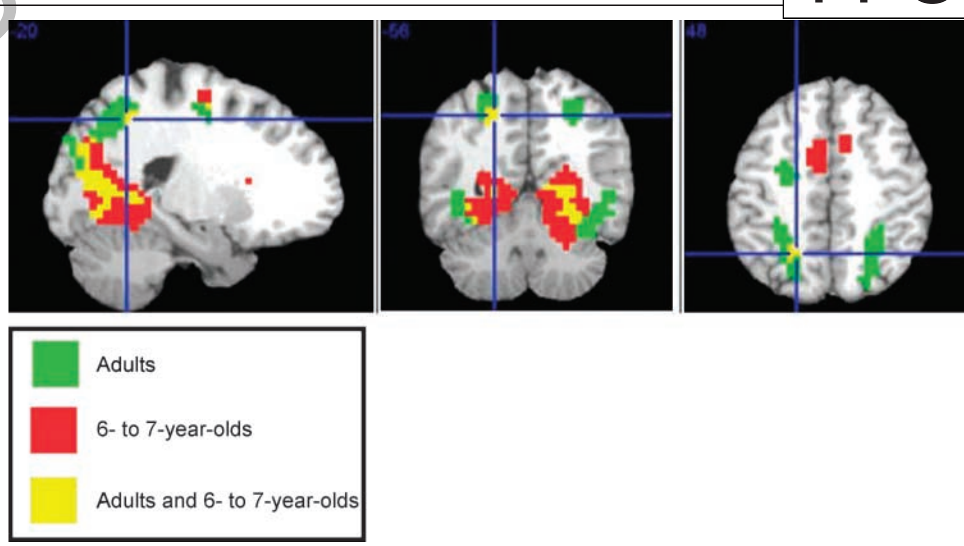

Figure 2. The conjunction analysis for Arabic numerals and dot arrays. Regions that exhibited a significant response to both Arabic numerals and dot arrays above baseline are shown for children and adults in the same image space ($p < .003$, 8 contiguous voxels). Children are shown in red, adults are in green, and regions where children and adults overlap are in yellow. Crosshairs converge on left superior parietal cortex (MNI coordinates: $-20x$, $-56y$, $48z$).

Table 1. Regions That Exhibited a Positive Response to *Both* Arabic Numerals and Dot Arrays

x	*y*	*z*	*t*	*Region*	*BA*
6- to 7-year-olds					
−24	−60	−8	5.66	Occipito-temporal cortex	18
16	−52	−12	5.28	Occipito-temporal cortex	18/19
−20	−48	−4	4.54	Occipito-temporal cortex	19/37
−47	−72	0	3	Occipito-temporal cortex	37
−24	20	12	4.11	Inferior frontal gyrus/insula	13
−32	12	16	3.66	Inferior frontal gyrus	44
48	16	12	4.03	Inferior frontal gyrus	44
40	12	16	3.75	Inferior frontal gyrus	44
40	0	32	3.46	Inferior frontal gyrus	44/9
−8	0	52	3.71	Precentral gyrus	6
−24	−12	56	2.73	Precentral gyrus	6
−8	−4	64	2.71	Precentral gyrus	6
−40	0	36	3.05	Precentral gyrus	6
8	−16	16	2.63	Thalamus	
−12	−20	16	2.59	Thalamus	
−20	−56	48	2.28	Superior parietal lobule	7
Adults					
44	−68	8	6.23	Occipito-temporal cortex	37
−48	−68	−4	6.09	Occipito-temporal cortex	37
−24	−60	48	5.44	Superior parietal lobule	7
−28	−8	52	3.92	Precentral gyrus	6
−40	−12	68	2.79	Precentral gyrus	6

Note that *t* values are from the second-level conjunction analysis.

in activity during both notations of numerical comparison for children and adults were occipito-temporal (OTC), precentral, and superior parietal cortices. Additionally, for children, this network included a region of the inferior frontal gyrus (IFG), bordering insular cortex, in both hemispheres (BA 44) and the thalamus.

We performed a between-groups comparison of the conjunction maps for children and adults within an image mask defined by Brodmann's areas that exhibited significant activity in the conjunction analysis for either children or adults (i.e., the union of the conjunction maps for children and adults). Of the regions that emerged from the conjunction analysis, a between-groups contrast of children versus adults revealed significantly greater activity for children in the IFG relative to adults (Figure 3, left panel). Adults, on the other hand, exhibited significantly greater activity than children in left superior parietal cortex (Figure 3, right panel). Thus, the regions of inferior frontal cortex that exhibited above-baseline activity during both kinds of numerical judgments in children did not differ from baseline in adults, whereas adults recruited parietal cortex more extensively than did children (although both groups exhibited activity in parietal cortex).

Next, we identified the voxels within the clusters reported in Table 1 that elicited the strongest activation to both Arabic numerals and dot arrays and tested these voxels for the effect of numerical ratio in children and adults. Our analysis took into account intersubject variability in the precise location of response peaks (see Piazza et al., 2004). For each subject, using the results of the conjunction analysis, we first isolated the 15 strongest voxels within a circumscribed region (radius = 15 mm), centered on the peak coordinates of each cluster identified in the first-stage group analysis. These voxels defined a subject-specific region of interest (ROI) at or near the group average peak. Maps displaying the voxels that contributed to this analysis for each group are shown in

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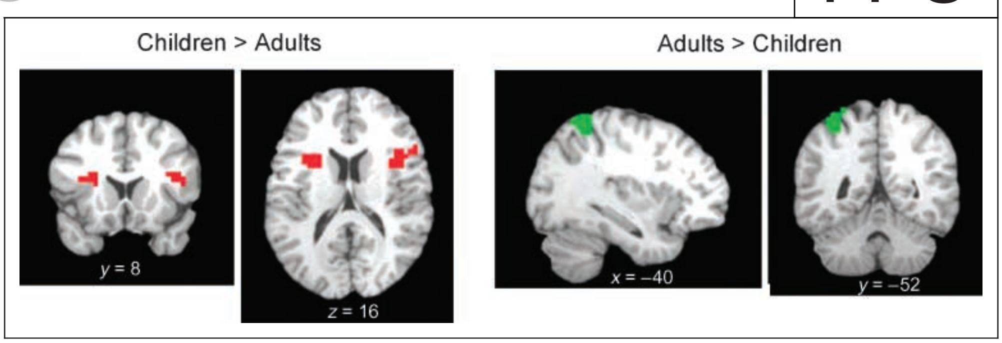

Figure 3. Statistical comparison of children and adults. Of regions that emerged from the conjunction analysis, children showed greater activity than adults, bilaterally, in the inferior frontal gyrus [left panel; 40*x*, 8*y*, 16*z*: cluster = 32 voxels, $t(28) = 3.47$, $p < .0001$; −32*x*, 12*y*, 16*z*: cluster = 21 voxels, $t(28) = 3.37$, $p < .0001$], whereas adults showed greater activity than children in left superior parietal cortex [right panel; −40*x*, −52*y*, −64*z*: cluster = 40 voxels, $t(28) = 4.11$, $p < .0001$].

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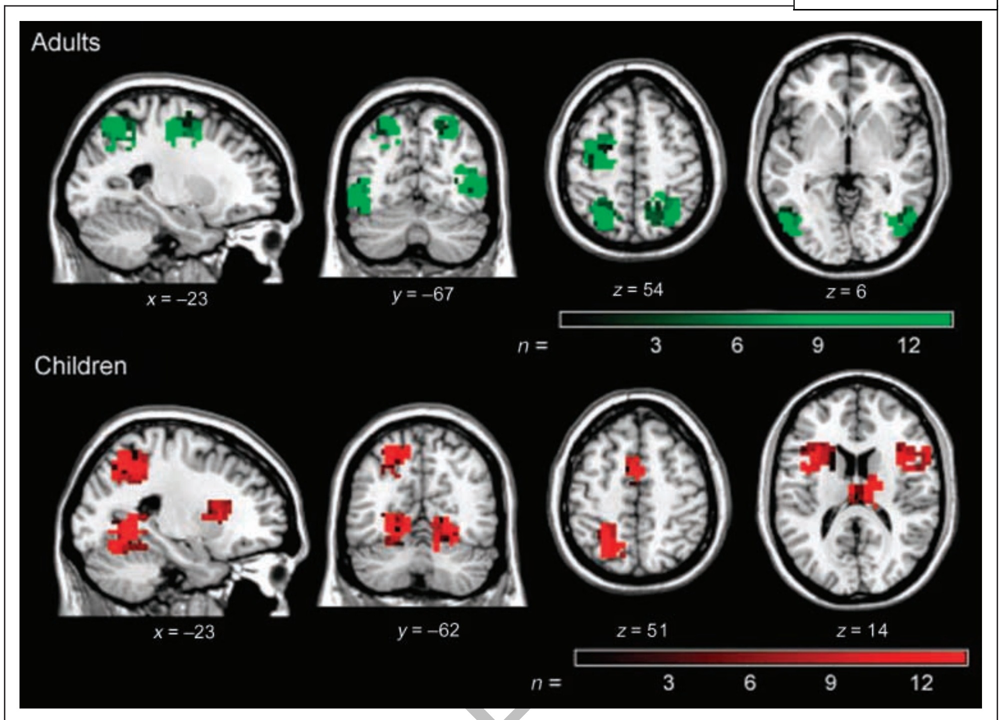

Figure 4. Voxels contributing to ROI analyses. The 15 strongest voxels for each subject within regions that emerged from the conjunction analysis are shown for adults (top) and children (bottom). The color bar shows the number of subjects (*n*) who had a given voxel in their top 15.

Figure 4. The average activation level of each individually drawn ROI was tested for the effect of numerical ratio. Note that the conjunction analysis used to define the voxels of interest in this analysis is orthogonal to the contrast of numerical ratio.

The results of this ratio effect analysis are shown in Figure 5. In adults, regions that evoked (1) a significant response to both Arabic numerals and dot arrays and (2) a significant numerical ratio effect included the precentral gyrus and superior parietal cortex. Children exhibited ratio-dependent activity in the IFG, the precentral gyrus, and the thalamus. Unlike adults, children did not exhibit a significant ratio effect in superior parietal cortex.

We examined the relationship between the numerical ratio effect in BOLD activity and the numerical ratio effect

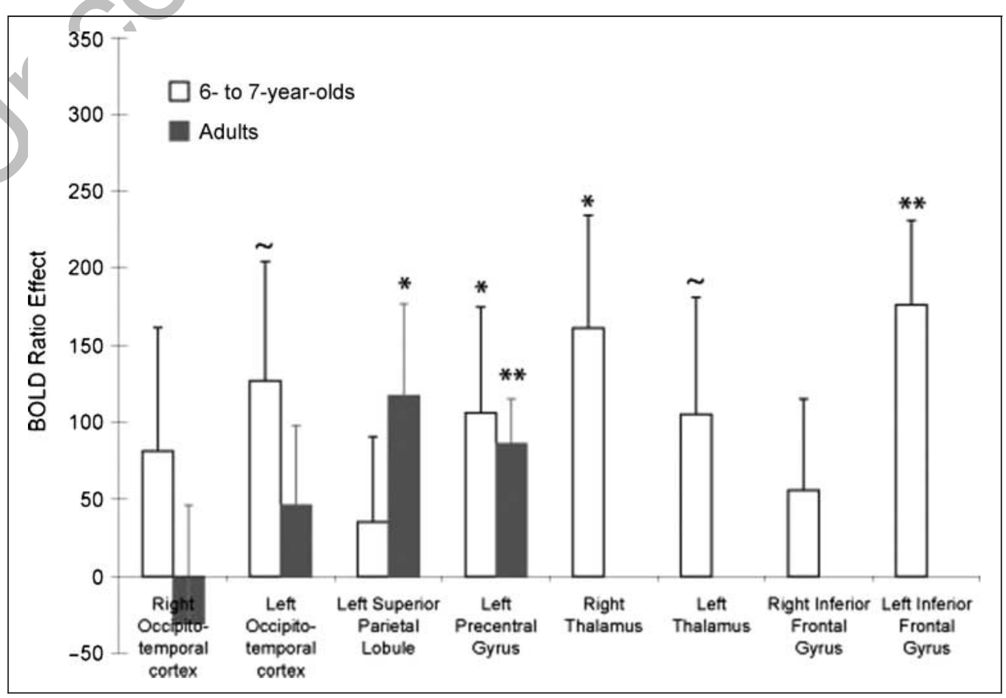

Figure 5. The numerical ratio effect. Of regions that exhibited a significantly positive response to Arabic numerals and dot arrays, a subset of regions also exhibited a significant effect of numerical ratio on BOLD activity. The strength of the numerical ratio effect in each region that survived the conjunction analysis is shown in gray bars for adults and white bars for children. $*p < .05$, $**p < .01$, $\sim p = .05–.08$. The *y*-axis represents the subjects' mean of the contrast-weighted sum of the beta values for the effect of numerical ratio.

in subjects' behavior by testing the strength of the BOLD ratio effect against individual differences in performance. Specifically, we measured the strength of each subject's behavioral ratio effect (accuracy on 0.5 ratio trials − accuracy on 0.8 ratio trials) against their BOLD ratio effect (β for contrast of 0.8 ratio > 0.5 ratio). We used accuracy as the primary performance measure because prior research has shown that response time reflects general decision-making processes beyond numerical processes in the intraparietal sulcus (e.g., Gobel et al., 2004). For adults, the ratio effect in BOLD signal did not correlate with individual differences in performance in any region (all *p*s > .05). Children, in contrast, showed a significant correlation between the behavioral and BOLD ratio effects in three regions: right OTC ($r = .53$, $p < .05$), left superior parietal cortex ($r = .49$, $p < .05$), and the IFG bilaterally (right: $r = .73$, $p < .01$; left = .47, $p < .05$). The results of these correlational analyses are shown in Figure 6.

Incidentally, although adults did not show a significant correlation between BOLD amplitude and accuracy in these regions, their correlations did not significantly differ from those of children in a χ^2 test (rOTC: $r = .53$ vs. .25; $\chi^2 = 0.62$, $p = .43$; left superior parietal: $r = .49$ vs. .16, $\chi^2 = 0.77$, $p = .38$). Nonetheless, the strength of the relationships between brain and behavior is stronger in children and reaches statistical significance.

The results of this correlation analysis demonstrate that in specific brain regions, physiological variability among children during numerical tasks is a reliable index of their performance. Importantly, children exhibited a correlation between the accuracy ratio effect and left parietal BOLD ratio effect despite the fact that there was no group-level ratio effect for children in this brain region. Thus, even in the absence of a group-level effect, children with stronger performance ratio effects exhibited stronger parietal ratio effects. The correlation between BOLD signal and behavior in children, in comparison to a lack of such an effect in adults, likely reflects the fact that early in development, behavioral ratio effects vary more widely among children (σ = 7%) than adults (σ = 2%).

To explore the functional connections among these brain regions, we examined the relative variability in the degree of ratio-dependent BOLD activity across children. First, the BOLD ratio effects in the two hemispheres of the IFG were strongly correlated ($r = .76$, $p < .001$). Secondly, the BOLD ratio effect in the IFG correlated with the BOLD ratio effect in left superior parietal cortex (right IFG: $r = .49$, $p < .05$; left IFG: $r = .35$, $p = .23$) and in right OTC (right IFG: $r = .52$, $p < .05$; left IFG: $r = .49$, $p < .05$). Lastly, there was no correlation between the BOLD ratio effect in left superior parietal cortex and OTC in children ($r = -.10$, $p = .74$). Interestingly, however, there was a correlation between BOLD activity in left superior parietal cortex and OTC in adults (right OTC: $r = .59$, $p < .05$; left OTC: $r = .49$, $p = .07$). In addition, the difference between children and adults in the strength of the correlation between parietal and OTC was marginally significant ($\chi^2 = 3.33$, $p = .07$). Thus, there was a significant link in activity between parietal cortex and OTC in adults but not in children.

Although this correlational analysis provides no directional information, these results implicate independent relationships in children between the IFG and parietal cortex on one hand, and the IFG and OTC on the other hand. The IFG was not active above baseline during numerical judgments of Arabic numerals and dot arrays in adults. Therefore, in children, the links between the IFG, parietal cortex, and OTC may reflect a central role for the IFG in the development of notation-independent numerical knowledge. One possibility is that the IFG plays an important role in linking numerical representations across notation systems early in development (Dehaene, 2008; Diester & Nieder, 2008).

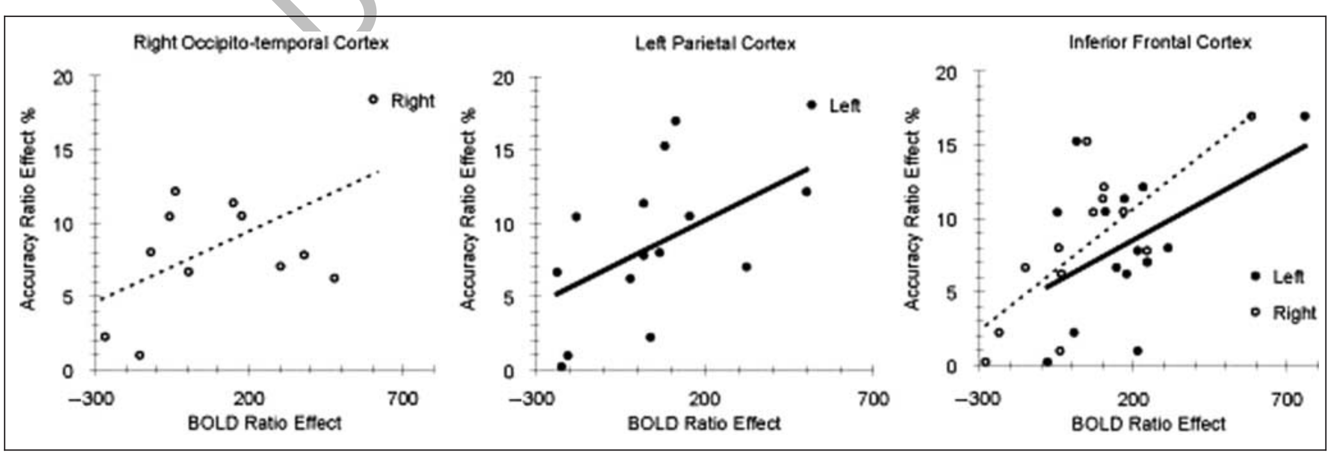

Figure 6. Brain–behavior correlations in the numerical ratio effect. Children showed significant correlations between the numerical ratio effect in their accuracy performance and the numerical ratio effect in their brain activity in right OTC, left superior parietal cortex, and bilateral inferior frontal cortex. The accuracy ratio effect is the difference in accuracy between the hard and easy ratio trials, whereas the BOLD ratio effect is the contrast-weighted beta value for the contrast of numerical ratio.

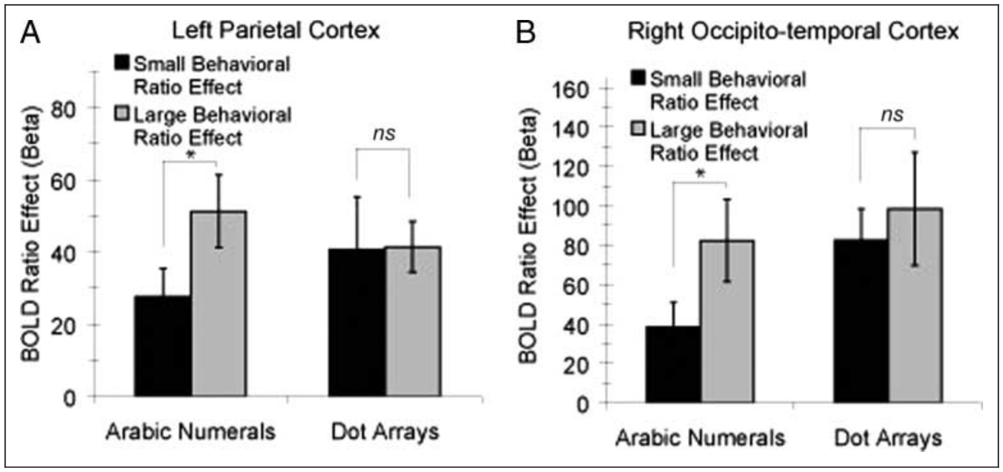

Figure 7. The numerical ratio effect for Arabic numerals versus dot arrays. Children were split into two groups based on the strength of the numerical ratio effect in their accuracy performance. Then we examined the ratio effect in brain activity for these groups of children (A and B), represented on the *y*-axis as the mean of the contrast-weighted sum of the beta values for the numerical ratio effect. When children were split according to their Arabic numeral performance, they exhibited significant differences in the BOLD ratio effect for Arabic numerals in left superior parietal cortex (A) and right OTC (B). There were no such differences in brain activity based on dot arrays performance. *$p < .05$, **$p < .01$, *ns* = not significant.

Because children exhibited a significant relationship between BOLD signal and behavioral performance, we conducted further analyses to explore differences in the ratio effect between Arabic numeral and dot array conditions. First, children performed significantly above chance on both the Arabic numerals [single-sample t test vs. chance (50%): mean = 81%, $SD = 0.12$, $t = 9.49$, $p < .0001$] and dot arrays comparisons (mean = 77%, $SD = 0.09$, $t = 11.02$, $p < .0001$). Next, we performed a median split on children's behavioral performance separately for Arabic numeral and dot array trials to examine the BOLD ratio effect in children who exhibited a large behavioral ratio effect compared to those who exhibited a small behavioral ratio effect. It is important to note that children in the small ratio effect group tended to show slightly lower overall accuracy (Arabic numerals: 80%; dot arrays: 76%) than children in the large behavioral ratio effect group (Arabic numerals: 82%; dot arrays: 78%).

Within the regions defined by the original conjunction analysis, we examined differences in BOLD activity between children in the two performance groups over the 15 voxels that exhibited the strongest ratio effect for each notation. For Arabic numerals, children in the small behavioral ratio effect group exhibited significantly less ratio-dependent BOLD activity compared to children in the large behavioral ratio effect group in left superior parietal cortex and right OTC (Figure 7A and B) but not in frontal cortex (Arabic numerals: $p = .15$; dot arrays: $p = .08$). There was no difference between the two groups of children in ratio-dependent BOLD activity in any of the queried brain regions for dot arrays (all ps > .08). For the median split on performance for dot arrays, there were no significant differences between children who showed a small ratio effect and those who showed a large ratio effect in any of the brain regions queried (all ps > .14).

The main conclusions that can be drawn from this analysis are (1) differences in performance on Arabic numeral judgments show more reliable differences in brain activity in regions involved in notation-independent numerical judgments than differences in performance for dot arrays and (2) the neural loci associated with group-level performance differences in Arabic numeral judgments are parietal cortex and OTC. This latter conclusion fits with neuropsychological and neuroimaging studies of adults showing that parietal cortex is a critical substrate for basic numerical cognition, including the ability to compare Arabic numerals (e.g., Pinel et al., 2004; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Dehaene & Cohen, 1997; see Dehaene et al., 2003 for a review), whereas regions of OTC are critical for object identification and the identification of written characters and symbols (e.g., Pernet, Celsis, & Démonet, 2005). Thus, differences between these children in parietal activity may be related to semantic processing of numbers, whereas differences in OTC activity may be related to visual processing of Arabic numerals.

DISCUSSION

This study provides novel information regarding the mechanisms underlying children's representation of ''numbers'' across visually distinct inputs such as arrays of dots or symbolic characters. The data indicate that children and adults engage a common constellation of cortical regions consisting of occipito-temporal, parietal, and precentral loci during numerical judgments of Arabic numerals and dot arrays. A similar cortical network has been identified by several prior studies of notation-independent numerical processing in adults (e.g., Piazza et al., 2007; Pinel et al., 2001, 2004; Dehaene, 1996; see Cohen Kadosh, Lammertyn, & Izard, 2008 for a review). However, unlike adults, 6- to 7-year-olds exhibited the strongest effect of notation-independent numerical processing in the IFG (BA 44). In children, this region generated a positive response to both Arabic numeral and dot array conditions, a robust numerical ratio effect, and a strong correlation with behavioral performance.

One proposal for the role of inferior frontal cortex in numerical judgments is that it may play a mediating role in the acquisition of abstract numerical knowledge over development. The proposition that frontal cortex participates in forming the initial links between symbolic and nonsymbolic numerical representations comes from single-cell studies in nonhuman primates reporting that cells in prefrontal cortex exhibit the properties of higher-order numerical categories (e.g., Diester & Nieder, 2007; Nieder & Merten, 2007; Nieder & Miller, 2003; Nieder, Freedman, & Miller, 2002; see Dehaene, 2008 for a review). For example, Diester and Nieder (2007) recorded the activity of posterior parietal and prefrontal neurons in nonhuman primates who were trained to associate Arabic numerals with nonsymbolic numerosities ranging from 1 to 4. That is, monkeys were trained to match visual arrays containing a certain number of elements with its corresponding Arabic numeral. Single neurons in parietal and prefrontal cortex elicited responses that were tuned to the numerical values of the nonsymbolic element arrays. Remarkably, the same prefrontal neurons that were tuned to the nonsymbolic numerical values also responded to the numerical value associated with the Arabic numeral, whereas parietal neurons did so only rarely (<2% of neurons). Thus, in monkeys, parietal and prefrontal neurons represent numerical values but, unlike parietal neurons, prefrontal neurons also represent the abstract association between a nonsymbolic numerical value and an Arabic numeral as its symbol.

Computational modeling experiments have built on neuroimaging and neurophysiological findings such as those described above to model the acquisition of notation-independent numerical concepts in humans (Verguts & Fias, 2004). These studies predict that abstract numerical knowledge is achieved via an initial period of associative learning between symbolic and nonsymbolic numerical representations, followed by the gradual acquisition and automatization of abstract numerical representations (Dehaene, 2008; Verguts & Fias, 2004). Building on this hypothesis, one possibility that arises from the current study is that children recruit inferior frontal cortex at an early stage of development to form associations among numerical values at a notation-independent level of abstraction.

Inferior frontal cortex appears to play a role in integrating information from a variety of neurocognitive domains to guide cognitive processes, abstract rule formation, and decisions in humans (e.g., Bunge, Kahn, Wallis, Miller, & Wagner, 2003; Cohen et al., 1997). Developmental studies have reported that at 8 to 12 years of age, children exhibit greater activity in and around this region than adults during sustained attention, mental comparison, dimension interference, and symbolic arithmetic tasks (e.g., Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006; Rivera et al., 2005; Casey et al., 1997). The emerging conclusion from these studies is that inferior frontal cortex is recruited more heavily by children than adults to coordinate and direct information related to abstract task goals. Therefore, the region of inferior frontal cortex recruited by children during the current experiment is not likely involved exclusively in numerical abstraction. However, this region may play an important role in the early developmental stages of numerical abstraction.

It is important to consider that although inferior frontal cortex is recruited during a variety of tasks, its role in these tasks may not be unitary over development. In the children tested in the current study, inferior frontal cortex responded to numerical values independent of notation and exhibited correlated activity with two other notation-independent brain regions: superior parietal cortex and OTC. Neither of these effects emerged in adults. This finding suggests that recruitment of all three of these brain regions might be especially important in the early stages of numerical development; either in a domain-general role such as working memory function or cognitive control (e.g., Crone et al., 2006; Rivera et al., 2005; Casey et al., 1997) or in a task-specific role such as the formation of abstract numerical "categories" (e.g., Diester & Nieder, 2007).

Although our results do not address the specificity of cortical regions for numerical processing, the results of several prior studies have converged on parietal cortex as a key substrate in the semantic representation of numerical values and other magnitude representations (e.g., Cohen Kadosh et al., 2005; Piazza et al., 2004; Nieder & Miller, 2003; Pinel et al., 2001; Butterworth, 1999; Dehaene, 1997; see Cantlon, Platt, & Brannon, submitted; Dehaene et al., 2003; Walsh, 2003 for reviews) as well as notation-independent numerical representations (Cohen Kadosh et al., 2007; Piazza et al., 2007). In the current study, adults exhibited notation-independent, ratio-dependent BOLD activity in left superior parietal cortex. Children also exhibited notation-independent BOLD activity in left superior parietal cortex, and specifically within the area of left parietal cortex that was active in adults. In addition, although notation-independent regions of parietal cortex were not modulated by numerical ratio in children at the group level, individual variability in the ratio-dependent BOLD activity of parietal cortex was correlated with individual differences in children's numerical performance.

Variability in children's knowledge of Arabic numerals was especially related to activity in parietal cortex. In addition, increased activity in the IFG predicted increased activity in parietal cortex. These findings may indicate that both parietal and inferior frontal cortices are recruited during notation-independent numerical concepts at early stages of development. In adulthood, in contrast, notation-independent numerical representations are hypothesized to automatically invoke parietal cortex, without the engagement of frontal cortex (see Dehaene, 2008). This proposition is reinforced by the lack of notation-independent number-related activity in frontal cortex in our adult subjects. Yet, the degree to which automaticity in numerical representation impacts brain activity over development requires further study.

Among children, activity in OTC also correlated with that of the IFG and exhibited a similar link with children's performance to parietal cortex during Arabic numeral comparisons. Activity in OTC was not correlated with activity in parietal cortex in children, whereas in adults, it was. Studies of visual processing in adults suggest that regions of OTC process the physical form of objects and symbolic characters (e.g., Pernet et al., 2005; Cohen, Jobert, Le Bihan, & Dehaene, 2004; Dehaene, 1996). An important question for future research is whether OTC plays parallel roles in symbolic and nonsymbolic numerical processing and how visual form processing affects children's developing numerical concepts.

Overall, the relationship between numerical performance and activity in notation-independent brain regions was stronger for Arabic numeral stimuli than arrays of dots in children. It is possible that performance differences for nonsymbolic numerical stimuli have idiosyncratic sources in the brain, whereas for symbolic numerical stimuli, performance differences among children arise from more uniform differences in specific brain regions. This interpretation agrees with our prior finding that brain activity related to numerical judgments of nonsymbolic numerical values begins to solidify very early in development, by at least 4 years of age (Cantlon et al., 2006), and therefore, may show less variability among older children. This explanation also accords with prior studies of symbolic numerical processing in older children that report greater engagement by frontal brain regions during Arabic numeral judgments in children than in adults (Ansari et al., 2005; Rivera et al., 2005).

The possibility remains that additional brain regions are involved in numerical processing for each notation system beyond those identified in the current study. In the current study, the numerical values presented in the Arabic numeral and dot array conditions were identical but the level of difficulty in each condition was not: Arabic numeral comparisons with these values were easier than dot array comparisons. Thus, the current study reveals commonalities between the two notation systems despite differences in their level of difficulty. Another approach would be to test for *differences* between numerical notations under conditions of equal difficulty. This alternative approach would help identify brain regions that are differentially involved in the cognitive processing of Arabic numerals and dot arrays over development.

In short, by 6 to 7 years of age, children recruit a common network of brain regions to adults during numerical comparisons of both symbolic and nonsymbolic numbers. However, our study demonstrates several key differences in the functions of this network between adults and children that implicate a role for the IFG in the early developmental stages of notation-independent numerical processing. Although the precise role of inferior frontal cortex in notation-independent numerical processing cannot be determined by our data alone, our data are consistent with the view that a core neural system processes the values of ''numbers'' throughout development but, early in development, higher-order brain mechanisms mediate this process.

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