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RESEARCH ARTICLE

Attention to number: The convergence of numerical magnitude processing, attention, and mathematics in the inferior frontal gyrus

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Abstract

Research indicates that the neurocognitive system representing nonsymbolic numerical magnitudes is foundational for the development of mathematical competence. However, recent studies found that the most common task used to measure numerical acuity, the nonsymbolic number comparison task, is heavily influenced by non-numerical visual parameters of stimuli that increase executive function demands. Further, this influence may be a confound invalidating theoretical accounts of the relation between number comparison performance and mathematical competence. Instead of acuity, the relation may depend on one's ability to attend to numerical information in the face of competing, non-numerical cues. The current study investigated this issue by measuring neural activity associated with numerical magnitude processing acuity, domain-general attention, and selective attention to number via functional magnetic resonance imaging while children 8–11 years old completed a nonsymbolic number comparison task and a flanker task. Results showed that activation in the right inferior frontal gyrus during incongruent versus congruent trials of the comparison task, our construct for attention to number, predicted mathematics achievement after controlling for verbal IQ, flanker accuracy rate, and the neural congruency effect from the flanker task. In contrast, activity in frontal and parietal regions responding to differences in difficulty of numerical comparisons, our construct for numerical magnitude processing acuity, did not correlate with achievement. Together, these findings suggest a need to reframe existing models of the relation between number processing and math competence to include the interaction between attention and use of numerical information, or in other words "attention to number."

KEYWORDS

attention, fMRI, inferior frontal gyrus, inhibition, mathematical concepts

1 | INTRODUCTION

A lack of competence in basic mathematics, also known as innumeracy, increases an individual's risk for unemployment (Parsons & Bynner, 2005; Rivera-Batiz, 1992), poverty (Hudson, Gross, & Price, 2009), and negative health outcomes (Duncan et al., 2007; Hibbard et al., 2007). For many, even with adequate resources, becoming numerate is extremely difficult (Butterworth & Laurillard, 2010). It requires mastery of a large range of skills over the course of years of schooling. As their foundation, mathematical skills require the training and cooperation of a host of neurocognitive mechanisms with functions ranging from perceiving and maintaining numerical information to the attentional demands of executing multistep mathematical procedures. Any one of these requisite mechanisms is a potential source of difficulty in the path to mathematical competence. One such proposed mechanism, often referred to as the approximate number system (Halberda, Mazzocco, & Feigenson, 2008) or number sense (Dehaene, 2011), is used for processing numerical magnitudes without reference to symbols, and has been the focus of a substantial body of research. That body of research suggests that atypical behavioral and neural metrics of magnitude processing are often associated with deficits in mathematical skill development (Iuculano, Tang, Hall, & Butterworth, 2008; Mazzocco, Feigenson, & Halberda, 2011a;

Mazzocco, Feigenson, & Halberda, 2011b; Mejias, Mussolin, Rousselle, Grégoire, & Noël, 2012; Mussolin, Mejias, Noël, & Noel, 2010; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007; Szkudlarek & Brannon, 2017; Wilson & Dehaene, 2007).

Behavioral measures of numerical magnitude processing relate to mathematics achievement across development and levels of mathematics achievement (Chen & Li, 2014; Schneider et al., 2017). However, recent findings indicate that those same measures of numerical acuity, and their subsequent relation to mathematics, may not be driven by magnitude processing mechanisms alone. Rather, the relation may depend on executive function demands introduced via visual properties of numerical stimuli, such as surface area or object size, that compete with discrete quantity for visual saliency in the dot arrays being compared (Gilmore et al., 2013). Specifically, inhibitory control has been shown to either account for a significant amount of variance in the relation between number comparison performance and mathematics achievement (Gilmore, Keeble, Richardson, & Cragg, 2015; Keller & Libertus, 2015) or explain the relation altogether (Fuhs & McNeil, 2013; Gilmore et al., 2013). How, then, are attentional mechanisms of executive function related to the processing of numerical magnitudes? And further, are they independently or jointly related to mathematical competence, if at all? The current study aims to investigate these questions by measuring neural activity associated with the neurocognitive constructs of numerical magnitude processing acuity, domain-general attention, and attention to numerical information.

The dominant theory for the link between numerical magnitude processing and mathematics achievement is that individuals with greater numerical acuity have an easier time estimating quantities and comparing magnitudes, which leads to greater faculty in handling numerical information in their symbolic form for use in mathematics (Dehaene, 2011). A convergence of evidence from neuroimaging in humans and cell recordings in animals suggests that neurons in the intraparietal sulcus (IPS) and ventrolateral prefrontal cortex are active during nonsymbolic comparison tasks and likely use population coding schemes to represent numerical magnitudes (Nieder, 2016; Sokolowski, Fias, Mousa, & Ansari, 2016). Supporting the numerical acuity account, these regions are frequently activated by higher-level mathematical tasks, such as subtraction and addition (Polspoel, Peters, Vandermosten, & De Smedt, 2017; Venkatraman, Ansari, & Chee, 2005), and individual differences in their functional activation and structural morphology have been related to mathematical competence (Bugden, Price, McLean, & Ansari, 2012; Price, Wilkey, Yeo, & Cutting, 2016; Rotzer et al., 2008). Further, behavioral research dissecting the amount of variance predicted by multiple aspects of stimulus dimension, including numerosity and conflicting visual cues, indicates that numerical acuity continues to be a predictor of mathematics achievement after controlling for other task dimensions, including inhibitory control (Keller & Libertus, 2015; Starr, DeWind, & Brannon, 2017).

A second possibility for the link between magnitude processing tasks and mathematics achievement relates mainly to individual differences in attention (Fuhs & McNeil, 2013; Gilmore et al., 2013). For example, during the number comparison process, attentional mechanisms are called upon to resolve competing visual cues, inhibiting irrelevant stimulus dimensions, and prioritizing numerosity as the salient visual feature for response selection. With this explanation, a cohort of individuals could possess the exact same numerical acuity but vary widely in their ability to inhibit competing stimulus features, resulting in a wide array of accuracy rates and response times in the number comparison task. And, because it has been well established that various components of executive function correlate with mathematics (Blair & Razza, 2007; Bull & Scerif, 2001; Espy et al., 2004), it would not be surprising that these metrics correlate with mathematics achievement. This account would explain why several studies have found that only performance on trials where visual parameters of stimuli conflict with numerosity, or *incongruent trials*, relates to math achievement (Gilmore et al., 2013, 2015) or the presence of a math learning disability (Bugden & Ansari, 2015). In this explanation, no actual reference to numerical acuity is necessary to explain the relation between nonsymbolic magnitude comparison performance and math competence. Recent work by Piazza, De Feo, Panzeri, and Dehaene (2018) uses behavioral data from samples with varying levels of development and math education to compare the impact of age and education on refinement of numerical acuity as compared to one's ability to focus on number. They find that both age and education primarily impact focusing on number rather than acuity, lending further support to the importance of attention-driven numerical processing.

Further, an explanation based on individual differences in attention may provide an alternate interpretation of neuroimaging findings in humans. Attention mechanisms and magnitude processing mechanisms largely converge in both frontal and parietal regions (Petersen & Posner, 2012; Sokolowski et al., 2016), including the bilateral IPS and inferior frontal gyrus (IFG), making it difficult to disentangle their respective contributions to task-related activity without strict controls and additional analyses. Differences in neural activation in the IPS or frontal regions in response to numerical stimuli may equally be driven by attentional demands that depend on task difficulty or resolution of conflicting visual cues, though at least one study found that congruency did not affect parietal response to numerical magnitudes (Wilkey, Barone, Mazzocco, Vogel, & Price, 2017).

While both magnitude processing and attentional mechanisms provide coherent candidates as foundational mechanisms for individual differences in mathematical competence, another possibility is a form of domain-specific attention, or *attention to number*. Rather than a generalized attentional component across domains, it may be that the way executive function mechanisms interact with magnitude processing mechanisms is a critical factor for acquiring mathematical competence, in addition to each mechanism's function considered independently. In regards to number comparison tasks, it may explain why performance on number comparison tasks relates to math achievement beyond non-numeric measures of executive function (Keller & Libertus, 2015) and also why congruent trials are less related to achievement than incongruent trials. However, within the construct of attention to number, there are multiple neural mechanisms that control attentional allocation. On the one hand, increased attention can be achieved by increasing the saliency of a particular percept, or in other words, turning up the gain for neural activity related to a particular stimulus dimension, such as number. This type of response has been demonstrated in multiple modalities, from hearing (Kerlin, Shahin, & Miller, 2010) to vision (Bisley, 2011; Hillyard, Vogel, & Luck, 1998). For example, covert attention to the left side of a fixation cross (i.e., no movement of the eyes) will increase neural response in the right extrastriate visual cortex, which corresponds to the left visual field (Mangun, Hopfinger, Kussmaul, Fletcher, & Heinze, 1997). On the other hand, increased attention to number could be achieved by suppressing competing perceptual information. For example, cell recordings in the lateral intraparietal area in monkeys show that overtly ignoring a stimulus dimension suppresses neural response in areas of the brain that control visual salience (Ipata, Gee, Gottlieb, Bisley, & Goldberg, 2006). These two mechanisms, that of increased gain and suppression of competing information, are likely to work in concert to direct attention to number in the context of a number comparison task. Less efficacy of their action may result in a deficit of attention to number.

One point of clarification is warranted regarding the current study's intentionally broad use of the construct of attention. The principal form of attention investigated in the current study, whereby a child was directed to respond to a choice in stimuli by isolating the correct visual dimension (i.e., number of dots or arrow orientation), is known by several names. A long history in cognitive neuroscience, espoused by Posner and Peterson (Petersen & Posner, 2012; Posner & Petersen, 1990), has delineated attention systems of the human brain based on anatomical organization, associated neurotransmitters, and their dissociable cognitive functions. In their model, the current tasks fall principally under the control of fronto-parietal "executive attention" and "orienting" networks. Psychologists, on the other hand, tend to use the term "executive function" to refer broadly to an array of top-down mental processes needed for concentration and paying attention (Diamond, 2014), which is further broken down into inhibition, working memory, and cognitive flexibility (Miyake et al., 2000). Thus far, research on the effect of congruency in number comparison tasks has mainly focused on inhibitory control components of executive function without much discussion of their underlying neural mechanisms (Clayton & Gilmore, 2014; Fuhs, Kelley, O'Rear, & Villano, 2016). However, we hypothesize that attention to number is likely to involve both increased focus of cognitive resources to numerical information and the inhibition of irrelevant information. Therefore, *attention to number* is a term we use to begin the conversation about domain-specific attention while leaving open the possibility that multiple neural mechanisms are captured by the paradigm utilized in the current study.

1.1 | The current study

The current study aims to investigate the relation between three neural mechanisms (i.e., numerical magnitude processing, attention, and attention to number) and mathematical competence. Based on the behavioral literature to date, it is clear that magnitude processing tasks relate to mathematical competence, but it is unclear what underlying neural mechanisms are responsible for this relation. To investigate this question, neural activity was measured via functional magnetic resonance imaging (MRI) while children 8 to 11 years of age completed a nonsymbolic number comparison task and an Eriksen flanker task. Contrasts were designed to capture magnitude processing (i.e., ratio effect) and attention to number during the number comparison task (i.e., numerical congruency effect) and attention in a non-numerical context during the flanker task (i.e., flanker congruency effect). Providing a neural measure of response to increased attentional demand in a numerical (number comparison) and non-numerical context (Flanker) allowed us to separate attentional components that have previously been considered principally as a singular, domain-general neurocognitive construct. Therefore, we specified a fourth contrast corresponding to the double subtraction of attention to number minus attention in a non-numeric context. Individual differences in neural measures of each construct were then related to mathematics achievement.

All three neurocognitive mechanisms specified in the current study may contribute to the acquisition of mathematical skills. Accordingly, fMRI measures of all three constructs may correlate with math achievement. Therefore, if individual differences in numerical magnitude processing acuity during the nonsymbolic number comparison predict mathematics achievement, we expect a correlation between the neural ratio effect and achievement in parietal magnitude processing brain regions. If differences in non-numerical, domain-general attention mechanisms predict mathematics achievement, we expect to see a correlation of achievement with individual differences in the flanker congruency effect within fronto-parietal attention network regions. However, behavioral research investigating the issue of congruency in number comparison tasks would suggest that attentional mechanisms are a critical component of the relation between numerical acuity and mathematics. Therefore, we hypothesized a strong relation between attention to number as captured by neural measures of the numerical congruency effect and mathematics in fronto-parietal attention and magnitude processing mechanisms, even after subtracting out the flanker congruency effect. Comparing each of the three constructs may provide an understanding of their unique contribution to individual differences in handling numerical information in typically developing individuals and a platform for identifying the origins of math learning deficits in atypical development.

2 | MATERIALS AND METHODS

2.1 | Participants

Children were recruited broadly from the greater metropolitan area via public announcements and Vanderbilt University study pools and were paid for their participation. Fifty-two typically developing children completed the current study. Of those, seven children were excluded from all analyses based on MRI quality assessment techniques (i.e., motion and signal artifacts, see *fMRI Analyses below for details*), two due to unavailable behavioral data during MRI acquisition, two due to accuracy on fMRI tasks below chance, and one was excluded due to misalignment of the bounding box which resulted in missing slices. The final sample thus consisted of 40 children (8.02–10.76 years, M = 9.27, 19 female). All participants were either in third or fourth grade with the youngest participants beginning the summer after completing second grade. The following exclusionary criteria were applied during the initial recruitment phase: (a) parent report of major health concerns, (b) parent report of developmental disability,

(c) known existing neurological or psychiatric problems including seizures and migraines, (d) known, uncorrected visual impairment, and (e) language other than English learned as primary language. Individuals with a reported diagnosis of attention deficit hyperactivity disorder (ADHD) (n = 3) were not excluded from participation and were instructed to maintain typical schedule of medications. Children with ADHD did not differ from the rest of the sample in any measure and principal fMRI analyses were checked for undue influence on results (Supporting Information Figure S3). All procedures conducted in this experiment were approved by the Institutional Review Board.

2.2 | Procedure

The study consisted of two testing sessions, a behavioral testing session with a mock scan and an MRI session. In the first, behavioral session we assessed performance on a range of academic, intelligence, and cognitive measures (Table 1) and concluded with a 20-min training session in the mock scanner to familiarize children with the scanner environment and experimental tasks. They then returned for the MRI scans on a second visit. Scans included a structural scan, three task-based fMRI scans, resting state, and a diffusion-weighted scan if time allowed.

2.3 | Behavioral assessment

2.3.1 | Mathematics achievement

Mathematical achievement was assessed using the Applied Problems, Math Fluency, and Calculation subtests of the Woodcock-Johnson III Tests of Achievement (Woodcock, McGrew, & Mather, 2001). The Applied Problems subtest is an untimed verbal and picture-based measure of a student's ability to analyze and solve math problems, beginning with the application of basic number concepts. The Math Fluency subtest requires participants to answer as many simple addition, subtraction, and multiplication problems as possible within a 3-min period. The Calculation subtest, on the other hand, is untimed, and requires participants to complete as many calculation items as possible that increase in difficulty, ranging from simple arithmetic to calculus. Grade-normed standard scores were used for all analyses. A composite mathematics achievement scores was created by taking the mean of the three grade-normed standard scores to capture a wide range of mathematics skills. Kolmogorov–Smirnov test of normality with Lilliefors significance correction demonstrated that all the math measures were normally distributed (all p values >0.072).

TABLE 1 Sample descriptive statistics, n = 40

	Mean	SD	Range
Age (years)	9.3	0.66	(8.0–10.8)
WCJ-III calculation (grade-normed)	111.7	16.1	(81–145)
WCJ-III math fluency (grade-normed)	100.8	14.5	(75–145)
WCJ-III applied problems (grade-normed)	112.4	13.8	(78–137)
Mathematics achievement (average of WCJ-III math measures)	108.3	12.6	(84–142)
Verbal IQ (KBIT-2)	114.1	13.6	(80–137)

WCJ-III = Woodcock Johnson III; KBIT-2 = Kaufman Brief Intelligence Test, 2nd edition.

2.3.2 | Intelligence quotient (IQ)

Nonverbal IQ, Verbal IQ, and Composite IQ estimates were obtained for each participant based on the Kaufman Brief Intelligence Test, second edition (Kaufman & Kaufman, 2004). The KBIT-II Verbal IQ is a comprised of a picture vocabulary section and a riddles section, while the nonverbal IQ includes a single section of matrix reasoning questions. Composite IQ is used to describe the sample and Verbal IQ is used as a control measure of domain-general intelligence theoretically unrelated to the spatial reasoning factors measured during the nonsymbolic comparison and flanker task.

2.4 | MRI session

On the second visit, children were rebriefed on MRI procedures and practiced the in-scanner tasks for 10 min before their MRI. During scanning, children's head were stabilized with headphones, foam padding, and medical tape. A research assistant, present during the first testing session, accompanied the child into the scan room for the duration of each imaging session. During each MRI session, children completed reference and anatomical scans, followed by two functional runs each of a symbolic number comparison task, a nonsymbolic number comparison task, and a flanker task with event-related designs. The order of tasks was counterbalanced across participants with all six possible task orders. Stimuli orders within tasks were consistent across participants. Only data from the nonsymbolic comparison task and the flanker task are analyzed in the current study. All tasks utilized left and right thumb buttons for responses.

2.4.1 | fMRI tasks

Nonsymbolic number comparison

Participants were presented with two sets of dots simultaneously and asked to indicate via button press which set was more numerous (i.e., which set contained more dots) (Figure 1). A button box was placed on each hand and participants responded with the thumb button of each box. Light gray dots (RGB value of 50, 50, and 50) were presented on a dark gray background (RGB value of 230, 230, and 230) divided by a vertical, black fixation line for a duration of 1,250 ms followed by a screen with just the fixation line for inter-stimulus intervals of 3,250, 4,250, 5,250, or 6,250 ms (M = 4,750 ms). Two ranges of ratios were presented, small and large (ratio = smaller number of dots divided by larger number). Small (easier) ratios ranged from 0.286 to 0.375 and large (more difficult) ratios ranged from 0.625 to 0.714. The number of dots in a given set ranged from 5 to 21. 40 small ratio and 40 large ratio trials were presented for a total of 80 trials. Response side, inter-stimulus interval, ratio, and congruency were counterbalanced. To control for the possibility that participants might choose a response based on visual cues rather than number of dots, the following visual properties of dot sets were varied using a modified version of the MATLAB code recommended by Gebuis and Reynvoet (2011) to generate stimuli: convex hull (area extended by a stimulus), total surface area (aggregate value of dot surfaces), average dot diameter, and density (convex hull divided by total surface area). In half of all trials convex hull, total surface area and dot diameter were greater for the greater of the two numerosities

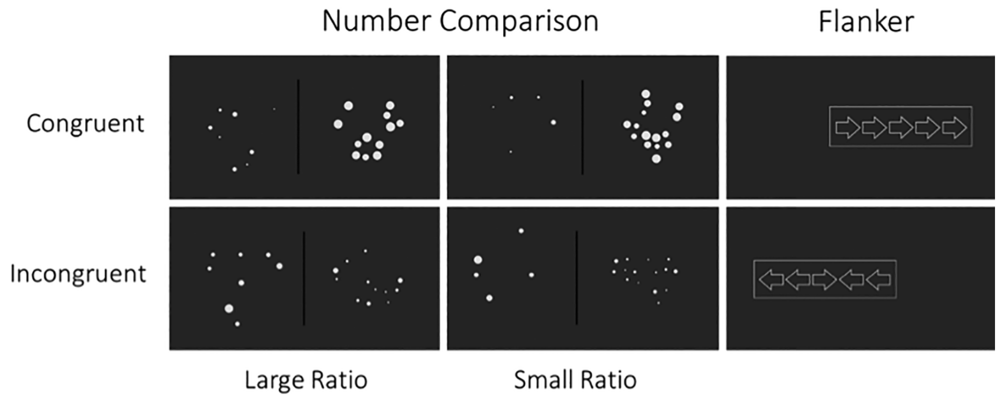

FIGURE 1 Example stimuli from the nonsymbolic number comparison (left and center) and flanker (right) tasks. Number comparison stimuli on the left are large ratio trials (i.e., more difficult ratios) and number comparison stimuli in the center are small ratio trials (i.e., easier ratios). Congruent trials from each task and condition are in the top row

presented (i.e., congruent), with the same parameters being incongruent for incongruent trials. Convex hull and surface area have demonstrated the greatest effect on behaviors (Clayton, Gilmore, & Inglis, 2015; Gilmore, Cragg, Hogan, & Inglis, 2016). Across the two runs, there were 20 trials of each of the following conditions: (a) congruent large ratio, (b) incongruent large ratio, (c) congruent small ratio, and (d) incongruent small ratio.

Flanker task

Participants were presented with a horizontal array of five arrows with the middle arrow pointing either in the same direction as the flanking arrows (i.e., congruent condition) or in the opposite direction as the flanking arrows (i.e., incongruent condition) and asked to indicate via button press which direction the middle arrow was pointed (Figure 1). Arrows were presented in the same light gray as the dots in the number comparison task against a background of dark gray for a duration of 1,250 ms followed by a blank dark gray screen for inters-stimulus intervals of 3,250, 4,250, 5,250, or 6,250 ms. 40 incongruent and 40 congruent trials were presented for a total of 80 trials. Response side, inter-stimulus interval, and congruency were counterbalanced across trials. In order to encourage saccadic eye movement similar to the number comparison tasks and prevent focusing only on the center of the screen, the array of arrows pseudo-randomly appeared centered on either the left or right side of the screen. Arrows were preceded by 200 ms by a fixation box that encompassed the arrows, allowing time for the children to orient to the stimulus with enough remaining time to successfully complete the task. Luminance across Flanker stimuli (the same for each trial) was equated with mean luminance across the nonsymbolic comparison task (different across trials).

2.4.2 | MRI acquisition parameters

All MR imaging was acquired with a Phillips Achieva 3T MR scanner (Andover, MA, USA) using a 32-channel head coil. Functional data was acquired using a multislice 2D SENSE T2* gradient-echo, echo planar imaging pulse sequence. Functional images were obtained in the axial plane with the following parameters: Repetition time (TR) = 2000 ms; Echo Time (TE) = 25 ms; voxel size = $2.5 \times 2.5 \times 3$ mm with an inter-slice gap of 0.25 mm; field of view = $240 \times 129.75 \times 240$ mm; imaging matrix = 96×96; flip angle = 90°; SENSE factor = 2.5. The whole brain was acquired in 40 slices with a slice thickness of 3 mm. To allow for steady-state magnetization to be reached before acquiring the functional data, five dummy volumes were added at the beginning of each scan, which were subsequently discarded. For the two nonsymbolic comparison runs, 133 volumes were collected for each run and each run had a duration of 279.9 s. For the two flanker task runs, 137 volumes were collected for each run and each run had a duration of 288.4 s. Inter-stimulus intervals were set at 3.25, 4.25, 5.25, or 6.25 s (mean = 4.75) for all runs. In the same session, a high-resolution T1-weighted, three-dimensional Magnetization Prepared Rapid Gradient Recalled Echo (MP-Rage) sequence was also acquired according to the following specifications: TR = 8.929 s; TE = 4.61 ms; flip angle = 8°; 170 sagittal slices with no inter-slice gap; voxel size = $1 \times 1 \times 1$ mm; imaging matrix = 256×256; acquisition time = 264.8 s. Scans were oriented in the anterior–posterior commissure plane.

2.4.3 | fMRI preprocessing

Images were analyzed using BrainVoyager Version 20.6.2.3266 (Goebel, Esposito, & Formisano, 2006) with preprocessing steps performed in BrainVoyager via in-house Python code and outlying volume detection using the Artifact Detection Tools (ART) toolbox as implemented in CONN toolbox (v17, www.nitrc.org/projects/conn, RRID:SCR_009550) (Whitfield-Gabrieli & Nieto-Castanon, 2012). Structural images were skull-stripped, corrected for inhomogeneities, and then normalized to MNI space (MNI-ICBM 152). Preprocessing of functional images consisted of slice scan time correction (cubic splice interpolation), motion correction with respect to the first volume in each run (tri-linear/sinc interpolation), and linear trend removal in the temporal domain (cutoff: 3 cycles). Functional images were aligned to T1 structural images using gradient-driven affine transformation in native space, with manual adjustments when needed, normalized into Montreal Neurological Institute (MNI) space using transformation matrices based on the transformation of structural images, and then spatially smoothed with a 6 mm full width at half maximum (FWHM) Gaussian kernel.

2.4.4 | fMRI analyses

Functional data were analyzed using a general linear model (GLM) and a random effect analysis for the group-level data. Experimental events were convolved with a standard two-gamma hemodynamic response function. Baseline was implicitly modeled as fixation time between trials. The GLM included six regressors of no interest that corresponded to the six motion parameters obtained during preprocessing. An additional covariate of no interest was created to account for variance associated with outlying volumes with volume-to-volume motion exceeding 1.5 mm or a mean volume intensity of 4 *SD*'s beyond the *z*-normalized global signal across runs as determined by the ART toolbox. Individuals with >25% of volumes flagged as outliers across both runs of each task (n = 6) were excluded from further analysis. One additional individual was excluded due to a large wraparound artifact identified through visual inspection of data. Incorrect trials in all tasks were modeled as separate predictors and excluded from subsequent analyses. Anatomical labels of results were defined by manually entering MNI converted peak coordinates into Jülich atlas probability maps within the Anatomy Toolbox v2.2b in SPM12 (Eickhoff et al., 2005).

Number, attention to number, and attention

The first set of analyses consisted of three whole-brain statistical contrasts of experimental conditions designed to capture neural activity related to (a) numerical magnitude processing, (b) attention to number, and (c) attention in a non-numerical context. First, to investigate neural activity related to the processing of numerical magnitudes, we contrasted large ratio trials with small ratio trials of the number comparison task. Second, to investigate neural activity related to attentional demands in a numerical context, we contrasted incongruent trials with congruent trials of the number comparison task. Third, to investigate activity related to attentional demands in a non-numerical context, we contrasted incongruent trials with congruent trials in the flanker task. All statistical results were thresholded at p < .005 and corrected for multiple comparisons at p < .05 using the cluster-level correction toolbox in BrainVoyager (Goebel et al., 2006), which estimates a cluster-level, false-positive rate based on a Monte Carlo simulation of 1,000 iterations.

Attention to number, controlling for non-numeric attention

To further investigate attention mechanisms specifically associated with numerical magnitude processing, a double subtraction was performed whereby the congruency effect in the flanker task was subtracted from the congruency effect in the number comparison task [(incongruent number comparison > congruent number comparison) − (incongruent flanker > congruent flanker)]. Incongruent trials on both tasks are thought to engage top-down, fronto-parietal inhibitory control mechanisms in order to direct attention to the relevant stimulus dimension, numerical magnitudes and orientation of the arrows, respectively (Amso & Scerif, 2015; Gilmore et al., 2013; Wilkey et al., 2017). Therefore, this subtraction should capture neural activity specifically involved in attending to numerical magnitudes beyond activity related to attentional demands in a similar, but non-numerical task.

Relation to mathematics achievement

To investigate how individual differences in neural measures of each construct related to mathematical competence, average β-weights from significant clusters in each of the three single contrasts were extracted at the subject level as regions of interest (ROI's) and correlated with the composite measure of mathematics achievement, controlling for verbal IQ, flanker accuracy, and age at time of scan utilizing partial correlations. Additionally, to investigate the relation of attention to number while controlling for non-numerical attention, beta weights from the double-subtraction were extracted and then correlated with mathematics achievement, controlling for verbal IQ, accuracy in the flanker task, and age at the time of scan. To investigate if other regions of the brain demonstrated individual differences in this specific contrast that were not significant at the group level, correlation was run with mathematics achievement as the covariate in a whole-brain ANCOVA. Similar to single contrast controls, Verbal IQ was controlled for by entering mathematics scores into a linear regression as the dependent variable with verbal IQ as a predictor and using unstandardized residuals as the covariate in a whole-brain ANCOVA. To control for verbal IQ, flanker performance, and age at time of scan, all measures were included in the regression to compute residuals. To correct for multiple comparisons, correlations use the Bonferroni method to adjust for the number of tests within in each set of neural contrasts (i.e., alpha for four cluster's = .05/4 = .0125). Corrected and unadjusted p values are presented.

3 | RESULTS

3.1 | Behavioral performance in MRI tasks

3.1.1 | Effects of ratio and congruency

Behavioral variables of interest from the fMRI tasks were response time (ms) for correct responses and percent accuracy across all trials in both the nonsymbolic comparison task and the flanker task (Figure 2). In line with previous results from similar nonsymbolic comparison tasks (Inglis & Gilmore, 2014; Merkley & Ansari, 2010; Price, Palmer, Battista, & Ansari, 2012; Price & Wilkey, 2017), individuals were more accurate for small ratio trials than large ratio trials [$t(39)$ = 11.35, p < .001, Cohen's d = 1.98] and for congruent trials than incongruent trials [t (39) = 6.25, p < .001, Cohen's d = 1.02]. Response times were greater for small ratios than large ratios [$t(39)$ = 8.08, p < .001, Cohen's d = 1.34] and greater for incongruent trials than congruent trials [t (39) = 9.34, p < .001, Cohen's d = 1.71] (within-subject adjusted Cohen's d; Morris & DeShon, 2002). In the flanker task, children were also more accurate for congruent trials [$t(39)$ = 7.25, p < .001, Cohen's d = 1.26] and had greater response times for incongruent trials [t (39) = 12.38, p < .001, Cohen's d = 2.02]. Effect sizes indicate that the size of the behavioral congruency effect was similar, but slightly larger for the flanker task as compared to the number comparison task.

3.1.2 | Number comparison, flanker task, and mathematics achievement correlations

Bivariate correlations were computed to assess the relation between fMRI task performance, age, mathematics achievement,

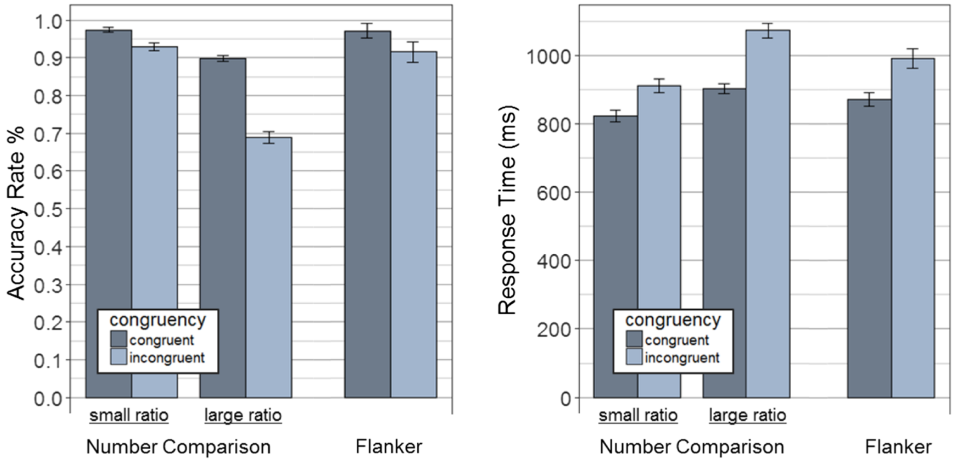

FIGURE 2 Nonsymbolic comparison and flanker behavioral data from fMRI tasks showing (left) accuracy rate (total % correct) and (right) response time, split by ratio bin (left/right) and congruency condition (light/dark blue) [Color figure can be viewed at wileyonlinelibrary.com]

and verbal IQ (Table 2). Of note, mathematics achievement was significantly correlated with verbal IQ, accuracy on number comparison, and accuracy on the flanker task. However, when separated by congruency, only the relation between incongruent trials on the number comparison task and mathematics achievement reached significance. In contrast, performance on congruent trials in the flanker task, and not incongruent trials, was significantly related to mathematics achievement. For significant bivariate correlations, partial correlations were also computed between mathematics achievement and task performance while controlling for Verbal IQ. All four task performance measures remained significant [number comparison, all trials $r(37) = .375$, $p = .019$; number comparison, incongruent trials $r(37) = .328$, $p = .042$; flanker, all trials $r(37) = .338$, $p = .035$; flanker, congruent trials $r(37) = .397$, $p = .012$]. Behavioral ratio effects (e.g., large ratio accuracy – small ratio accuracy) and congruency effects (incongruent mean accuracy – congruent mean accuracy) were also computed for both accuracy and response times in both tasks and correlated with mathematics achievement. No ratio effect or congruency effect correlations with mathematics were significant [all p's > .277]. Partial correlations controlling for age are presented in Supporting Information Table S2 and largely reflect the bivariate correlations.

3.2 | fMRI results

3.2.1 | Number comparison ratio effect

The contrast of large ratio trials (i.e., more difficult ratios) compared to small ratio trials revealed four regions with significantly greater activity for large ratio trials including the right middle frontal gyrus (rMFG), right inferior frontal gyrus *pars triangularis* (rIFG), right IPS, and right superior medial gyrus (Figure 3a, Table 3). All four of these regions were task-positive (i.e., above the implicit baseline activation level) on average. Three regions showed significantly greater activity for small ratio trials, including the right angular gyrus, left middle temporal gyrus, and left supramarginal gyrus.

3.2.2 | Number comparison congruency effect

The contrast of incongruent trials in the number comparison task (i.e., those where visual parameters conflicted with greater

TABLE 2 Correlations between behavioral measures and MRI task performance

Measure (n = 40)	1	2	3	4	5	6	7	8
1. Age								
2. Mathematics achievement	−.267							
3. Verbal IQ (KBIT-2)	.119	.331*						
4. Number comparison (all trials, accuracy)	.061	.366*	.038					
5. Number comparison (incongruent accuracy)	.037	.324*	.045	.876***				
6. Number comparison (congruent accuracy)	.064	.237	.007	.662***	.219			
7. Flanker (all trials, accuracy)	.240	.378*	.196	.526***	.429*	.398*		
8. Flanker (incongruent accuracy)	.203	.279	.126	.505**	.413*	.380*	.946***	
9. Flanker (congruent accuracy)	.244	.447**	.259	.447**	.363*	.341*	.869***	.662***

*p < .05, **p < .01, ***p < .001.

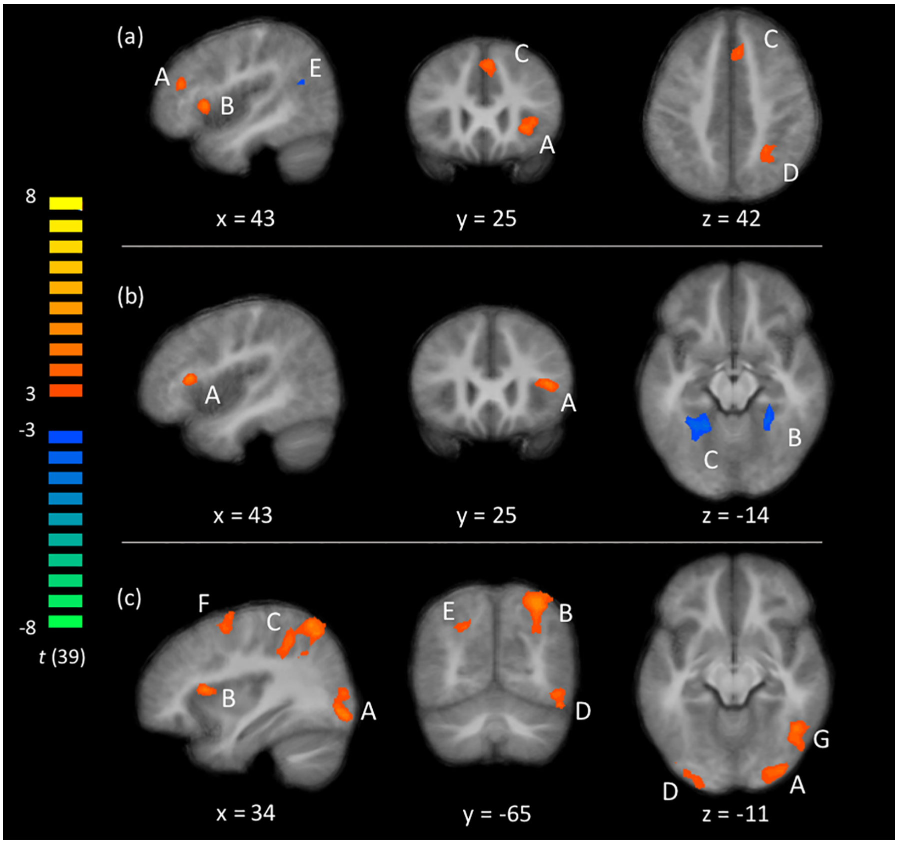

FIGURE 3 Results from contrasts of (a) number comparison large ratios > small ratios, (b) number comparison incongruent > congruent, and (c) flanker incongruent > congruent. All maps are cluster corrected at $p < .05$, uncorrected $p < .005$. Cluster details are presented in Tables 3, 4, and 5, respectively. Slices labeled in MNI space and presented in neurological convention [Color figure can be viewed at wileyonlinelibrary.com]

numerosity) compared to congruent trials revealed one region with greater activity for incongruent trials, the rIFG, and three regions with greater activity for congruent trials, in the bilateral fusiform gyrus and right primary visual cortex (Figure 3b, Table 4).

3.2.3 | Flanker congruency effect

The contrast of incongruent trials in the flanker task (i.e., trials with flanking arrows in opposite directions from the central arrow) compared to congruent trials revealed seven regions with greater activity

TABLE 3 Significant clusters for contrast of large ratio > small ratio trials in number comparison task

Cluster	Peak MNI (*x, y, z*)	Voxels	Peak *t* (mean *t*)	Large β	Large SE	Small β	Small SE	BA	Anatomical description
Positive effects = (large ratio > small ratio)									
A	(48, 38, 19)	902	4.74 (3.43)	1.16	0.19	0.51	0.21	46	R MFG
B	(42, 20, 4)	2,298	4.55 (3.54)	1.44	0.19	0.69	0.20	45	R IFG (*P. triangularis*)
C	(3, 23, 46)	1,480	4.08 (3.23)	1.36	0.24	0.72	0.23	8	R Sup. Med. Gyrus
D	(27, −49, 43)	1,160	3.88 (3.19)	1.77	0.27	1.14	0.23	7	R IPS (*hIP1*)
Negative effects = (small ratio > large ratio)									
E	(51, −67, 22)	808	−4.22 (−3.28)	−0.51	0.17	−0.16	0.19	39	R AG (*PGp*)
–	(−60, −58, 4)	1,177	−4.38 (−3.43)	−0.45	0.21	0.07	0.19	39	L MTG
–	(−69, −31, 28)	1,143	−3.93 (−3.24)	−0.10	0.19	0.43	0.18	40	L SMG (*PF*)

MNI = peak coordinates in MNI-ICBM 152; Large = large ratio (more difficult) trials; Small = small ratio (easier) trials; BA = Brodmann area. β values are means extracted at the cluster level. R = right; L = left.
*All results cluster corrected at $p < .05$, uncorrected $p < .005$ (clusters > 740 voxels, 1 mm iso). Clusters with letters are represented in Figure 3. Anatomical description abbreviations in italics refer to Juelich atlas labels.

TABLE 4 Significant clusters for contrast of incongruent > congruent trials in number comparison task

Cluster	Peak MNI (*x, y, z*)	Voxels	Peak *t* (mean *t*)	INC β	INC SE	CON β	CON SE	BA	Anatomical description
Positive effects = (incongruent > congruent)									
A	(45, 23, 10)	1,216	5.25 (3.49)	0.37	0.18	−0.26	0.18	45	R IFG (*P. triangularis*)
Negative effects = (congruent > incongruent)									
–	(11, −103, −2)	1,169	−4.87 (−3.43)	1.83	0.25	2.31	0.25	17	R primary visual (*V1, hOc1*)
B	(24, −46, −17)	725	−4.20 (−3.33)	0.63	0.21	1.04	0.18	37, 20	R fusiform gyrus (*FG3*)
C	(−21, −49, −14)	2,128	−4.23 (−3.33)	0.85	0.22	1.38	0.19	37, 20	L fusiform gyrus (*FG3*)

MNI = peak coordinates in MNI-ICBM 152; INC = incongruent trials; CON = congruent trials; BA = Brodmann area; R = right; L = left.
*All results cluster corrected at p < .05, uncorrected p < .005 (clusters >598 voxels, 1 mm iso). β values are means extracted at the cluster level. Clusters with letters are represented in Figure 3. Anatomical description abbreviations in italics refer to Juelich atlas labels.

for incongruent trials (Figure 3c, Table 5). These regions included large portions of the bilateral superior parietal lobe centered in each hemisphere's IPS, bilateral early visual processing areas in the occipital lobe, the right insula, rMFG, and the right inferior temporal gyrus. Of note, the cluster in the right anterior insula is medial to both rIFG clusters resulting from the number comparison ratio effect and congruency effect contrasts. However, the flanker congruency effect does partially overlap with the number comparison congruency effect where the rIFG and right insula meet. There is no overlap between the flanker congruency effect with the ratio effect contrast in the rIFG (for overlay, see Supporting Information Figure S1).

3.2.4 | Attention to number

The double subtraction of the congruency effect in the number comparison task minus the congruency effect in the flanker task, designed to capture neural activity related to attending to numerical magnitudes beyond non-numerical attentional demands, revealed five regions with a significant effect (Figure 4, Table 6). Three of the regions were similar to (i.e., largely overlapping with) those present in the single subtraction of incongruent compared to congruent conditions of the number comparison task (i.e., also present in Table 4): the rIFG, the right primary visual cortex, and left fusiform gyrus. As in the single subtraction, the resulting t-statistic in each of these three regions continued to be positive for the rIFG and negative for the right fusiform and occipital regions. One region, the left inferior occipital gyrus (V2), largely overlaps with the left middle occipital gyrus of the congruency effect in the flanker task, with the double subtraction resulting in a negative t-statistic. Further, one region in the precentral gyrus was unique to the double subtraction.

3.2.5 | Correlation of single contrasts with mathematics achievement

To investigate the relation between individuals differences in neural measures of (a) numerical magnitude processing (i.e., ratio effect), (b) attention to number (i.e., number comparison congruency effect), and (c) attention in a non-numerical context (i.e., flanker congruency effect) and mathematics achievement, cluster-level β-weights from the significant regions in each of the contrasts were extracted for each subject and correlated with the composite mathematics achievement score. Results indicated that individual differences in each of the seven regions in Table 3 showing a significant ratio effect did not correlate with mathematics achievement before controlling for verbal IQ

TABLE 5 Significant clusters for contrast of incongruent > congruent trials in flanker task

Cluster	Peak MNI (*x, y, z*)	Voxels	Peak *t* (mean *t*)	INC β	INC SE	CON β	CON SE	BA	Anatomical description
A	(39, −82, −5)	3,364	5.77 (3.58)	3.99	0.36	3.53	0.35	19	R inferior occipital gyrus (*hOc4lp*)
B	(30, 17, 10)	1,420	5.52 (3.67)	1.12	0.19	0.61	0.20	13	R insula
C	(30, −64, 55)	8,230	5.38 (3.52)	2.02	0.21	1.39	0.18	7	R SPL (*7A, hIP3*)
D	(−33, −91, 7)	3,805	5.33 (3.48)	3.91	0.31	3.42	0.28	18	L middle occipital gyrus (*hOc4lp*)
E	(−24, −61, 37)	1,291	4.44 (3.36)	1.52	0.22	1.02	0.20	7	L IPS (*hIP3, hIP1*)
F	(36, 2, 55)	1,288	4.40 (3.34)	1.87	0.21	1.41	0.20	6	R MFG
G	(45, −55, −11)	1,988	4.37 (3.35)	2.34	0.20	1.79	0.17	37, 20	R ITG (*FG4*)

MNI = peak coordinates in MNI-ICBM 152; INC = incongruent trials; CON = congruent trials; BA = Brodmann area; R = right; L = left.
*All results cluster corrected at p < .05, uncorrected p < .005 (clusters >740 voxels, 1 mm iso). β values are means extracted at the cluster level. Clusters with letters are represented in Figure 3. Anatomical description abbreviations in italics refer to Juelich atlas labels.

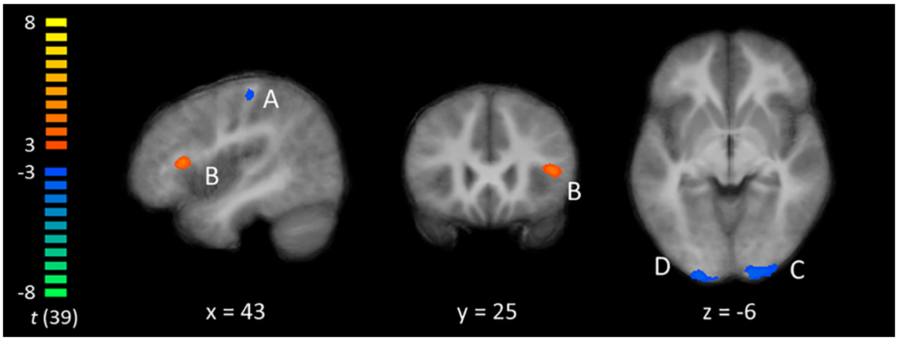

FIGURE 4 Results from double subtraction contrast of congruency effect in number comparison > congruency effect in flanker task. All maps are cluster corrected at $p < .05$, uncorrected $p < .005$. Cluster details are presented in Table 6. Slices labeled in MNI space and presented in neurological convention [Color figure can be viewed at wileyonlinelibrary.com]

[all p's > .453] or after [all p's > 0.279], even before controlling for multiple comparisons. For the four regions demonstrating a significant congruency effect in the number comparison task in Table 4, only the rIFG demonstrated a significant correlation with mathematics achievement [$r(38) = -.468$, $p = .002$, Bonferroni-adjusted $p = .008$; all other p's > .292, unadjusted]. The correlation with activity in the rIFG was negative, meaning that higher mathematics scores correlated with less difference in neural activation between incongruent and congruent trials of the number comparison task. The relation in the rIFG remained essentially unchanged after controlling for verbal IQ [$r(37) = -.474$, $p = .002$, Bonferonni-adjusted $p = .008$)] and stronger after controlling for verbal IQ, mean accuracy on the flanker task, and age [$r(35) = -.521$, $p = .001$, Bonferonni-adjusted $p = .004$]. Regarding the last neural contrast, the flanker congruency effect, correlation results indicated that individual differences in one of the seven clusters in Table 5, the middle occipital gyrus, significantly related to mathematics achievement. Similar to the congruency effect in the number comparison task, a lesser difference between incongruent and congruent β-weights correlated with higher mathematics scores [$r(38) = -.441$, $p = .004$, Bonferroni-adjusted $p = .028$] which remained significant after controlling for verbal IQ and age [$r(36) = -.438$, $p = .006$, Bonferroni-adjusted $p = .042$]. The flanker effect in one other region,

TABLE 6 Significant clusters for double subtraction of congruency effect in number comparison > congruency effect in flanker task

Cluster	Peak MNI (x, y, z)	Voxels	Peak t	Mean t	BA	Anatomical description
Positive effects						
B	(45, 23, 10)	1,000	5.58	3.60	45	R IFG (*P. triangularis*)
Negative effects						
C	(21, −100, 1)	2,110	−4.89	−3.53	17	R primary visual (*V1*)
D	(−24, −100, −11)	1,399	−4.82	−3.46	18	L inferior occipital gyrus (*V2*)
-	(−27, −49, −14)	587	−3.82	−3.22	37, 20	L FG (*FG3*)
A	(45, −22, 58)	583	−3.69	−3.16	4	R postcentral gyrus

MNI = peak coordinates in MNI-ICBM 152; BA = Brodmann area; R = right; L = left.
*All results cluster corrected at $p < .05$, uncorrected $p < .005$ (clusters >581 voxels, 1 mm iso). Clusters with letters are represented in Figure 4. Anatomical description abbreviations in italics refer to Juelich atlas labels.

the right middle frontal gyrus, showed a correlation with mathematics achievement, but did not survive correction for multiple comparisons before controlling for verbal IQ and age [$r(38) = -.315$, $p = .048$, Bonferroni-adjusted $p = .336$] or after [$r(36) = -.313$, $p = .056$, Bonferroni-adjusted $p = .392$]. All other regions showed uncorrected correlation p's > .061, unadjusted.

3.2.6 | Correlation of attention to number with mathematics achievement

To investigate the relation between individual differences in neural measures of attention to number while controlling for the neural response to attentional demands in a similar, but non-numeric task, cluster-level β-weights from the significant regions in the double subtraction of the number comparison congruency effect minus the flanker congruency effect were extracted for each subject and correlated with the composite mathematics achievement score. Of the five regions showing a significant group-level effect in Table 6, only activity in the rIFG showed a correlation that approached significance [$r(38) = -.369$, $p = .019$, Bonferroni-adjusted $p = .095$; all other p's > .528 unadjusted]. The correlation had a similar effect size after controlling for verbal IQ [$r(37) = -.370$, $p = .020$, Bonferroni-adjusted $p = .10$] and for verbal IQ, flanker accuracy rate, and age [$r(35) = -.355$, $p = .024$, Bonferroni-adjusted $p = .155$]. Considering the single contrast of the numerical congruency effect correlated with mathematics achievement at $r = -.468$, we interpret the current effect size of $r = -.355$ to continue to indicate a meaningful relation while acknowledging that the conservatively corrected p value does not reach significance.

Further, to test if individual differences in *attention to number* correlated with mathematics achievement in regions that may not have demonstrated a group-level effect, a whole-brain correlation was run with the double subtraction as the neural contrast of interest and the composite measure of mathematics achievement as the behavioral measure of interest. This analysis was repeated while controlling for verbal IQ, and then again controlling for verbal IQ, accuracy rate on the flanker task, and age, in an effort to control for factors related to general academic achievement unspecific to mathematics. Results indicate a significant negative correlation in another region of the rIFG, *pars orbitalis* (Table 7, top section), which remains significant after controlling for verbal IQ, mean accuracy on the flanker task, and

TABLE 7 Correlation of double subtraction of congruency effect in number comparison greater than congruency effect in flanker task with composite mathematics achievement score

Cluster	Peak MNI (x, y, z)	Voxels	Peak r	Mean r	BA	Anatomical description
Correlation with math achievement						
–	(30, 35, −14)	1,034	−0.55	−0.48	47	R inferior frontal gyrus (*P. orbitalis*)
Correlation with math achievement controlling for verbal IQ						
A	(39, 35, −8)	1,471	−0.61	−0.49	47	R inferior frontal gyrus (*P. orbitalis*)
B	(−12, 38, 1)	1,025	−0.52	−0.46	33	L anterior cingulate cortex
C	(−36, 35, 34)	1,291	−0.58	−0.48	9	L middle frontal gyrus
Correlation with math achievement controlling for verbal IQ, flanker accuracy, and age						
–	(39, 35, −8)	2,337	−0.64	−0.49	47	R inferior frontal gyrus (*P. orbitalis*)
–	(−24, 17, 19)	972	−0.62	−0.49	45	L inferior frontal gyrus (*P. triangularis*)
–	(−6, 2, 7)	1,887	−0.60	−0.48	–	L caudate
–	(−39, 26, 37)	1,471	−0.60	−0.49	46	L middle frontal gyrus
–	(36, 5, 28)	934	−0.56	−0.48	44	R inferior frontal gyrus (*P. opercularis*)

MNI = peak coordinates in MNI-ICBM 152; BA = Brodmann area; R = right; L = left.
*All results cluster corrected at $p < .05$, uncorrected $p < .005$ (clusters >598 voxels, 1 mm iso). Anatomical description abbreviations in italics refer to Juelich atlas labels.

age (Table 7, middle and bottom sections). Figure 5 displays results from the correlation controlling for verbal IQ. The resulting region in the rIFG, *pars orbitalis*, does not overlap with rIFG clusters demonstrating a neural ratio effect and numerical congruency effect though a smaller cluster in the right *pars triangularis* does, but does not survive cluster correction (overlay of maps detailed in Supporting Information Figure S1 at uncorrected $p < .005$).

4 | DISCUSSION

Deficits in attention and the processing of numerical magnitudes have both been linked to difficulties in acquiring numeracy (Fias, Menon, & Szucs, 2013; Geary, Hoard, Nugent, & Bailey, 2013; Mazzocco et al., 2011a; Mazzocco & Thompson, 2005; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013). However, little is known about the neural mechanisms that support their integration and how they relate to mathematical behaviors. The current study tested the hypothesis that *attention to number*, a construct representing this integration, achieved through the biological interaction of attentional mechanisms with numerical magnitude processing mechanisms, is a source of individual differences important for the development of mathematical skills. As previous studies have reported, accuracy rates on incongruent trials of the nonsymbolic number comparison task correlated with mathematics achievement, while accuracy rates on congruent trials did not. Further, while the neural ratio effect, a potential measure of magnitude processing acuity, did not relate to mathematical achievement, the numerical congruency effect negatively correlated with achievement in the rIFG after controlling for verbal IQ, performance on the flanker task, and age. This relation continued to show a moderate to small correlation after subtracting out activation related to the congruency effect in the flanker task. Therefore, behavioral and neuroimaging results support our hypothesis that there are specific neural substrates associated with *attention to number*, the activity of which relates to math competence over and above numerical acuity or domain-general attention alone. These findings call into question previously held assumptions about the relation between magnitude processing mechanisms and mathematical competence, detail an alternative explanation for the relation between nonsymbolic number comparison task performance and mathematics achievement, and

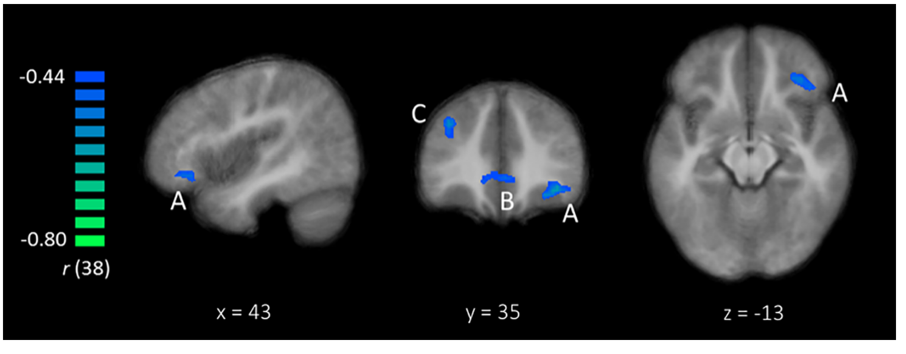

FIGURE 5 Results from contrasts of correlation of mathematics achievement composite score with double subtraction of congruency effect in number comparison greater than congruency effect in flanker task. All maps are cluster corrected at $p < .05$, uncorrected $p < .005$. Cluster details are presented in Table 6. Slices labeled in MNI space and presented in neurological convention [Color figure can be viewed at wileyonlinelibrary.com]

build the groundwork for future research investigating neural mechanisms related to *attention to number* as a potential source of difficulties related to math-specific learning disabilities.

4.1 | Numerical magnitude processing, attention to number, and attention

Results from the three single contrasts of interest in the current results largely support previously published results. Areas of the ventrolateral prefrontal cortex, medial anterior cortex, and right IPS demonstrated task-positive ratio effects, similar to meta-analyses of number processing tasks (Sokolowski et al., 2016), indicating their functional role in numerical magnitude perception. Results for incongruent > congruent trials are similar to the only two previous studies to execute a comparable contrast with the nonsymbolic number comparison task (Leibovich, Vogel, Henik, & Ansari, 2016; Wilkey et al., 2017) in that all three showed significantly greater activity during incongruent trials in the rIFG and Wilkey et al. (2017) also showed similar effects in the fusiform gyrus, although those previous studies involved adults and adolescents, respectively. A large body of work supports the notion that a right-lateralized portion of the inferior frontal cortex is critical for inhibiting response tendencies more generally and orienting to behaviorally relevant stimuli (reviewed in Aron & Poldrack, 2005; Aron, Robbins, & Poldrack, 2014; for meta-analysis see Levy & Wagner, 2011). However, in the current results, the numerical congruency effect in the rIFG is significant in the single contrast and continues to be significant at the group level when subtracting out activity related to the flanker effect in the double subtraction. The flanker task was designed to elicit response inhibition and task interference effects similar to the numerical congruency effect, but in a non-numerical context. Therefore, if modulation of the rIFG were a generalizable effect of inhibition, we would expect the effect to significantly diminish or disappear. When subtracting the flanker effect, instead, results show a similar, but slightly greater peak and mean *t*-values in the rIFG, indicating that the relation is specific to the number comparison task. Further, the contrasts of large > small ratio and incongruent > congruent trials of the number comparison task overlap in the rIFG, *pars triangularis*, suggesting the location is involved in numerical magnitude encoding. This interpretation fits with previous studies reporting a numerical ratio effect in both symbolic and nonsymbolic numerical formats (Ansari & Dhital, 2006; Cantlon et al., 2009) in the rIFG, particularly in children. Therefore, increased activity in the rIFG, *par triangularis*, during incongruent trials may reflect the allocation of more attentional resources, and therefore greater BOLD response, to a region of the cortex encoding numerical information. Alternatively, this increase in rIFG may also be representative of the increased allocation to numerical magnitudes itself. In other words, this region may be involved in the upregulation of neural representations of numerical magnitude elsewhere in the cortex or it may be the region encoding numerical magnitudes. In either case, we would expect a significant ratio effect and congruency effect. In contrast, decreased activity to the bilateral fusiform gyri and primary visual cortex may represent a suppression of activity related to non-numerical visual factors of the stimuli such as overall surface area and convex hull.

Lastly, results for the congruency effect in the flanker task showed similar results to three previous analyses of the flanker effect in children, which demonstrated greater activity for incongruent than neutral trials in the right IPS (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Vaidya et al., 2005) and bilateral occipital gyri (Konrad et al., 2005), though a similar lateralization in the left IFG and left insula to Bunge et al. (2002) was not replicated. As in all three studies of the flanker effect in children compared to adults, the anterior cingulate in the current study did not show a significant congruency effect, which is typical of response interference tasks in adults (Houdé, Rossi, Lubin, & Joliot, 2010; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). In short, results indicate a strong congruency effect consistent with previous studies, and therefore provide justification for the use of this contrast as a method of controlling for non-numerical attentional allocation associated with inhibition and interference control.

4.2 | Relations to mathematical competence

Most studies relating neural correlates of numerical magnitude processing to mathematical competence have focused on group comparisons between typically developing children or adults and individuals with dyscalculia (Dinkel, Willmes, Krinzinger, Konrad, & Koten, 2013; Kovas et al., 2009; Kucian, Loenneker, Martin, & von Aster, 2011; Price et al., 2007), and provide little consensus about which neurocognitive mechanisms drive the number comparison task's relation to mathematics. The two studies relating a similar neural contrast to math achievement in typically developing young adults and high school students (Gullick, Sprute, & Temple, 2011; Wilkey et al., 2017) found inverse ratio effects correlated with math achievement in bilateral insula, and inferior parietal regions, regions not canonically associated with the processing of numerical information. With the recent array of behavioral data indicating that incongruent trials drive the relation between task performance and mathematics achievement (Bugden & Ansari, 2015; Fuhs & McNeil, 2013; Gilmore et al., 2013; Prager, Sera, & Carlson, 2016), evidence is mounting in favor of the importance of executive function mechanisms and their interaction with magnitude processing mechanisms as a foundation for mathematical competence. The current results lend support to this interpretation in that none of the neural contrasts associated with magnitude processing alone (i.e., balanced for congruency) correlate with mathematics achievement, while the numerical congruency effect in the rIFG, *pars triangularis*, an area which demonstrated a significant ratio effect and numerical congruency effect, does correlate with mathematics achievement. The negative correlation, showing individuals with a lesser congruency effect are better at mathematics, could indicate a more effortful response in the inhibition process or protracted development of mechanisms related to attention to number. However, it should be noted that whereas the single contrast of the numerical congruency effect showed a significant correlation with mathematics achievement when controlling for verbal IQ and performance on the Flanker task with an effect size of $r = -.537$, the ROI-based double contrast showed a weaker effect size of $r = -.365$ that dropped below our significance threshold when controlling for multiple comparisons. This could indicate that a substantial portion of the congruency effect in the *par triangularis* which correlated with mathematics achievement resulted from domain-general processes.

The whole-brain correlation of mathematics achievement with the double-subtraction of the numerical congruency effect minus the flanker congruency effect similarly indicated the importance of attentional components of the task. However, the strongest correlation at the whole-brain level was an inverse correlation between a more inferior and anterior portion of the rIFG, the *pars orbitalis*, which did not overlap with the *pars triangularis* region displaying a significant ratio and congruency effect. The presence of two regions in the rIFG with a numerical congruency effect that negatively correlated with mathematics achievement, one of which demonstrates a ratio effect, may indicate that the rIFG is responsible for an array of mathematically relevant functions related to attention to number. Multiple aspects of executive function are thought to be orchestrated by the rIFG and its cortico-thalamic connections. A meta-analysis of neuroimaging data of cognitive control tasks by Levy and Wagner (2011) suggests that specific forms of cognitive control, such as the detection of relevant stimulus parameters and decision uncertainty, are subserved by distinct subregions of the rIFG. The current results, at the ROI level and in the whole-brain analysis, show that neural response of attention to number relates to mathematical competence in two regions of the rIFG, both the *pars triangularis* and *pars orbitalis*. Therefore, it may be that multiple attentional components dedicated to numerical magnitude processing are subserved by distinct subregions of the rIFG.

4.3 | Attention to number and spontaneous focusing on number

It should be noted that a substantial body of research originating with Hannula-Sormunen and colleagues has identified the spontaneous, self-initiated attentional focus on numerosity (SFON) as a strong predictor of math development (for a review, see Rathé, Torbeyns, Hannula-Sormunen, De Smedt, & Verschaffel, 2016). However, the construct of *attention to number* differs from SFON in several regards. For example, while attention to number refers to the neurocognitive mechanisms controlling attention to numerosity, SFON may be thought of a disposition toward exact number that an individual carries into any given scenario. Accordingly, any measure of SFON must be taken in the absence of explicitly numerical task demands. In contrast, neurocognitive mechanisms underlying attention to number may be utilized spontaneously or under explicit instruction. As a second point of difference, SFON research focuses on smaller numerosities that children are capable of counting quickly and exactly (Hannula, Lepola, & Lehtinen, 2010) whereas numerical magnitude processing often requires approximation of larger quantities. In other words, SFON refers to the tendency of an individual to notice numerical features of a given scene, while attention to number to refers to an individual's ability to upregulate number-specific neural processes, or inhibit non-numerical neural representations, in order to extract numerical information from a specific stimulus, especially in the case of competing information.

4.4 | Future directions

The current study utilizes a contrast based on numerical ratio in the number comparison task to identify areas of the brain associated with magnitude processing and then assumes that individual differences in this contrast would capture individual differences the associated neural substrate. However, little evidence exists that neural measures at standard resolutions of fMRI during the number comparison task are capable of indexing a neural measure of numerical acuity that is thought to be captured by behavioral indices of numerical acuity, such as accuracy or weber fraction. A greater neural ratio effect has been argued to indicate greater efficiency (Bugden et al., 2012) and also lesser efficiency (Gullick et al., 2011) of numerical magnitude processing mechanisms, but the underlying biological origin of each of these effects remains poorly understood. Only one study to date has related acuity of neural representation (i.e., neural tuning curves in the IPS) to behaviors measuring perceptual sensitivity, but this study did not include a measure of math achievement and largely avoided the confound of attention with the use of an adaptation paradigm with sequential presentation of stimuli (Kersey & Cantlon, 2017). However, the approach taken by Kersey and Cantlon may provide more information for a detailed account of numerical acuity in the future.

Two further issues should be taken into account in future studies of this topic. First, an exploration of both structural and functional connectivity between neural structures that support executive function and magnitude processing may provide an explanation of the role of subregions of the IFG. This may elucidate the actual role of the IFG *pars triangularis* as either a substrate for direct encoding of numerical information or as a region involved in the regulation of regions that encode numerical information. Second, executive function and numerical magnitude processing are both known to undergo substantial development during the early elementary school years (Ansari, Garcia, Lucas, Hamon, & Dhital, 2005; Davidson, Amso, Anderson, & Diamond, 2006). Executive function is known to increasingly involve the integration of a fronto-parietal and cingulo-opercular network (Fair et al., 2007; Fair et al., 2009). Therefore, in the current study, individual differences may be a result of naturally varying neural development or the development of mathematical skills. More research across development is needed to draw the link between differences in neural signatures and biologically plausible accounts of their corresponding behavioral significance.

More broadly, the current results demonstrate the importance of integrating the role of domain-general cognitive processes, such as attention, inhibition, and working memory, into existing models of number processing, such as the triple code model (Dehaene, 1992). There exists a gap in knowledge between representation of number and the use of that representation during problem solving, which inevitably relies on the above-mentioned domain-general cognitive processes. By addressing this gap in knowledge, new models of numerical cognition can begin to incorporate the dynamic interactivity of the brain, and more directly address the impaired behaviors that lead to poor mathematical skills and adverse life outcomes.

5 | CONCLUSIONS

The present findings support previous behavioral studies suggesting that attentional components of the nonsymbolic number comparison task are an important factor for its relation to mathematical competence (Bugden & Ansari, 2015; Fuhs & McNeil, 2013; Gilmore et al., 2015), as indicated by a stronger correlation between mathematics achievement and performance on incongruent trials of the number comparison task than congruent trials. Further, fMRI results suggest that individual differences in neural activity in the rIFG specifically involved in numerical magnitude processing measured during incongruent versus congruent trials of the number comparison task, our construct of *attention to number*, correlate with mathematics achievement. In contrast, neural activity in frontal and parietal regions associated with differences in ratio difficulty, our construct for numerical magnitude processing acuity, does not correlate with mathematics achievement. Therefore, behavioral and neuroimaging evidence from the current study suggest that *attention to number*, or the ability to upregulate number specific neural representations or inhibit non-numerical neural representations, are an important predictor of mathematical competence, over and above numerical magnitude processing or domain-general attention alone.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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