NeuroImage 159 (2017) 430–442

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

The effect of visual parameters on neural activation during nonsymbolic number comparison and its relation to math competency

Eric D. Wilkey [a], Jordan C. Barone [a], Michèle M.M. Mazzocco [b], Stephan E. Vogel [c], Gavin R. Price [a,*]

[a] Department of Psychology & Human Development, Peabody College, Vanderbilt University, 230 Appleton Place, Nashville, TN, 37203, USA
[b] Institute of Child Development, University of Minnesota, USA
[c] Educational Neuroscience, Institute of Psychology, University of Graz, Austria

ARTICLE INFO

Keywords:
Math competency
Nonsymbolic number comparison
Ratio effect
Magnitude perception
Angular gyrus
Supramarginal gyrus

ABSTRACT

Nonsymbolic numerical comparison task performance (whereby a participant judges which of two groups of objects is numerically larger) is thought to index the efficiency of neural systems supporting numerical magnitude perception, and performance on such tasks has been related to individual differences in math competency. However, a growing body of research suggests task performance is heavily influenced by visual parameters of the stimuli (e.g. surface area and dot size of object sets) such that the correlation with math is driven by performance on trials in which number is incongruent with visual cues. Almost nothing is currently known about whether the neural correlates of nonsymbolic magnitude comparison are also affected by visual congruency. To investigate this issue, we used functional magnetic resonance imaging (fMRI) to analyze neural activity during a nonsymbolic comparison task as a function of visual congruency in a sample of typically developing high school students ($n = 36$). Further, we investigated the relation to math competency as measured by the preliminary scholastic aptitude test (PSAT) in 10th grade. Our results indicate that neural activity was modulated by the ratio of the dot sets being compared in brain regions previously shown to exhibit an effect of ratio (i.e. left anterior cingulate, left precentral gyrus, left intraparietal sulcus, and right superior parietal lobe) when calculated from the average of congruent and incongruent trials, as it is in most studies, and that the effect of ratio within those regions did not differ as a function of congruency condition. However, there were significant differences in other regions in overall task-related activation, as opposed to the neural ratio effect, when congruent and incongruent conditions were contrasted at the whole-brain level. Math competency negatively correlated with ratio-dependent neural response in the left insula across congruency conditions and showed distinct correlations when split across conditions. There was a positive correlation between math competency in the right supramarginal gyrus during congruent trials and a negative correlation in the left angular gyrus during incongruent trials. Together, these findings support the idea that performance on the nonsymbolic comparison task relates to math competency and ratio-dependent neural activity does not differ by congruency condition. With regards to math competency, congruent and incongruent trials showed distinct relations between math competency and individual differences in ratio-dependent neural activity.

1. Introduction

Several large-scale, longitudinal studies indicate that math skills at school entry are a strong predictor of later academic achievement (Duncan et al., 2007; Geary et al., 2013) and socioeconomic status (Ritchie and Bates, 2013). Measured later in life, they are linked to employment status (Goodman et al., 2015) and even physical and mental health (Parsons and Bynner, 2005). In an effort to understand individual differences in math ability, much research has focused on the perception of numerical magnitudes. As a result, it has been well established that individual differences in the processing of numerical magnitude correlate with and predict later math achievement (Chen and Li, 2014; Schneider et al., 2016). And yet, the neural mechanisms underlying the link between processing of numerical magnitude and more advanced mathematical thought remain poorly understood.

Our understanding of this link relies on a relatively small set of

* Corresponding author.
E-mail address: gavin.price@vanderbilt.edu (G.R. Price).

http://dx.doi.org/10.1016/j.neuroimage.2017.08.023
Received 14 April 2017; Received in revised form 4 August 2017; Accepted 6 August 2017
Available online 8 August 2017
1053-8119/

experimental paradigms, most notably an array of nonsymbolic number comparison tasks, whereby a participant judges which of two groups of objects, such as dots or squares, is more numerous. Performance on this task is often assumed to reflect the precision of a mental representation of numerical magnitude (Halberda et al., 2008). Already, diagnostic tools for math learning disability (Butterworth and Laurillard, 2010; Nosworthy et al., 2013) and early learning interventions (Szűcs and Myers, 2016) are being developed which target measurement of and training of the nonsymbolic number system. However, in light of recent findings, these efforts may be premature. At least three behavioral studies have reported that unintended consequences of controlling the visual parameters of stimuli in the nonsymbolic comparison task have a significant influence on the relationship between task performance and math achievement (Bugden and Ansari, 2015; Fuhs and McNeil, 2013; Gilmore et al., 2013), thus complicating the link between magnitude perception and math. In other words, it is currently unclear whether the mechanism linking nonsymbolic comparison performance and math is in fact the precision of magnitude representation, or rather alternative cognitive mechanisms related to the processing of visual stimulus parameters. In order to understand the link between this potential confound in the nonsymbolic comparison task, the basic systems that encode numerical magnitude in the brain, and their link to math achievement, a detailed understanding of the neural mechanisms underlying the influence of visual cues on the perception of numerical magnitudes is essential. With this understanding, diagnostic tools and interventions may target specific neurocognitive mechanisms underlying math skills. Without it, they are at risk of targeting behaviors that merely correlate with math achievement but are not fundamental to its development.

1.1. Numerical magnitude processing efficiency & math competency

Most models of numerical magnitude perception begin with object identification that then feeds into a summation code, which abstracts number of objects over object position (see Nieder, 2016; for a review). The summation code then feeds into a number-selective code where populations of neurons in the superior parietal lobe have Gaussian response functions with peaks tuned to specific magnitudes (Nieder and Dehaene, 2009; Verguts and Fias, 2004). This number-selective code forms the basis of the "Approximate Number System" (ANS, Dehaene, 1997). Accordingly, numbers that are closer together in magnitude have more overlapping neural representation compared to numbers that are further apart, which are thought to be more distinct in neural representation. As a result, people are slower and less accurate when discriminating between numbers that are closer together in numerical magnitude versus those that are further apart. This 'ratio effect' can be modeled as a function of the numerical ratio between number pairs (Piazza et al., 2004). Therefore, in principle, to measure individual differences in this system's acuity, one need only measure the degree of overlap in the distribution of neighboring magnitude response functions. The nonsymbolic number comparison task attempts to do this by measuring accuracy rates and response times as participants judge which of two groups of objects is more numerous. In general, a smaller effect of ratio on accuracy and reaction time, or even simply higher accuracy rates and lower response times, are thought to indicate increased precision of the ANS (De Smedt and Gilmore, 2011).

Beginning with a retrospective study by Halberda, Mazzocco, & Feigenson (Halberda et al., 2008) that linked performance on the nonsymbolic number comparison task in 9th grade to math achievement in Kindergarten through 6th grade, a number of studies have supported the claim that ANS acuity is related to math abilities ranging from counting to arithmetic to algebra (Chen and Li, 2014; Schneider et al., 2017) and that reduced ANS acuity may represent a core deficit in the math learning disability developmental dyscalculia (Mazzocco et al., 2011; Piazza et al., 2010). Several neuroimaging studies also provide evidence for this link. For example, compared to typically developing children, children with dyscalculia show less modulation due to numerical magnitude in the right intraparietal sulcus (IPS) (Price et al., 2007), a region that has consistently been linked to numerical magnitude encoding (Sokolowski et al., 2016). Atypical activation patterns in other brain regions during this task have also been associated with dyscalculia including parieto-occipital regions (Dinkel et al., 2013), supplementary motor area and fusiform gyrus (Kucian et al., 2011), and inferior parietal regions (Kaufmann et al., 2009). Further, neural correlates of the ratio effect during nonsymbolic numerical comparison have also been linked to individual differences in math achievement in a typically developing population (Gullick et al., 2011), though in the study by Gullick and colleagues, the neural ratio effect is negatively correlated with math.

1.2. Confounding factors from visual controls

Although the research discussed above points to a link between ANS acuity, as indexed by nonsymbolic number comparison performance, and math ability, recent research suggests that the relationship may be related to processes other than ANS acuity alone. To ensure that participants respond to number comparison trials on the basis of numerosity rather than other visual cues that often covary with numerosity, such as surface area or density, researchers regularly control for these visual cues. The most common method of control is to create stimuli in which the surface area of the dots is either congruent with the correct choice (i.e. the dot set with the larger surface area is the dot set with the larger numerosity) or incongruent (i.e. both dot sets have the same surface area and the more numerous dot set has smaller dots) (Dehaene et al., 2005). Behavioral studies show that when selecting the larger of two sets, performance is significantly influenced by non-numeric visual properties of the stimulus such that individuals are slower to respond and less accurate in the face of incongruent visual information (Gebuis and Reynvoet, 2012; Szűcs et al., 2013). One theory posits that these non-numeric visual cues require participants to inhibit their visually-based response before making a quantity-based judgment (Clayton and Gilmore, 2014). Both Gilmore et al. (2013) and Fuhs and McNeil (2013) found that only performance on incongruent trials of the nonsymbolic number comparison task was related to symbolic math achievement, in primary school and preschoolers respectively. In both studies, this correlation was no longer significant after controlling for inhibitory control measured during tasks not related to numerical magnitudes. In a study of individuals with dyscalculia, Bugden and Ansari (2015) showed that differences in ANS acuity between dyscalculic and typically developing children were only found when analyzing incongruent trials of the nonsymbolic number comparison task. Though inhibitory control was not measured, Bugden & Ansari's results showed a close relationship between visuo-spatial working memory and performance on incongruent trials only in individuals with dyscalculia, indicating that working memory function during incongruent trials may be important for the relationship between nonsymbolic comparison and math. The results of these three studies indicate that the link between performance on nonsymbolic comparison tasks and math achievement may be explained by cognitive processes used to extract numerical magnitude from stimuli in the face of conflicting visual information rather than simply the representational acuity of the ANS.

Recent neuroimaging evidence of the nonsymbolic comparison task indicates that recruitment of neural resources also differs as a function of congruency condition. In a study of typically developing adults, Leibovich et al. (2015) showed that incongruent trials are associated with greater activity in the superior frontal gyrus and left inferior/middle frontal gyri, but less activity in the right middle temporal and posterior cingulate gyri, than congruent trials. However, Leibovich et al. (2015) examined activation during numerical versus non-numerical processing as a function of congruency, as opposed to examining the effect of congruency on ratio-dependent task activity. In order to investigate how differences in congruency specifically relate to processing of numerical information, the effect of congruency on magnitude-specific activation must be evaluated. Just as a behavioral ratio effect has become a hallmark measure of ANS acuity, ratio-dependent activation in the superior parietal lobe has become a neural proxy (i.e. the neural ratio effect) (Bugden et al., 2012). However, no study to date has investigated if the neural ratio effect during nonsymbolic numerical magnitude processing is affected by the congruency of visual cues, and consequently, whether these potential differences in neural activity relate to math achievement. Understanding how differences in congruency require the recruitment of unique neural resources or how they differentially recruit known magnitude processing mechanisms may shed light on why numerical magnitude encoding appears to be related to math competency only in the face of conflicting visual cues, as well as elucidating the precise role of parietal mechanisms in nonsymbolic numerical magnitude processing.

1.3. The current study

To investigate this issue, we conducted a series of whole-brain analyses using functional magnetic resonance imaging (fMRI) data from a nonsymbolic comparison paradigm run on a typically developing sample (n = 38) of twelfth grade students. First, in order to build on previous research, we investigated the degree to which neural activity is modulated by the ratio of nonsymbolic comparison trials. Second, we investigated differences in neural activity during the task according to visual control condition (i.e. congruent vs. incongruent). Lastly, we correlated the neural ratio effect across the whole brain with math achievement, as measured by the math section of the preliminary scholastic aptitude test (PSAT) and assessed whether correlations between the neural ratio effect and math achievement differed as a function of congruency. In regards to our first analysis, we expected to see increased task-related activity in the intraparietal sulcus and superior parietal regions and the inferior frontal gyrus, likely as a result of greater engagement of numerical magnitude processing, and also increased activity in the anterior cingulate, motor, and motor planning areas as a result of increased task difficulty with more difficult ratios. For our second series of analyses, we hypothesized that there would be greater overall activation and a stronger neural ratio effect during incongruent as compared to congruent trials in the inferior frontal gyrus and superior parietal lobule. For our last set of analyses, which correlated the neural ratio effect with math achievement, we hypothesized that individual differences in the neural ratio effect would correlate with math achievement in the superior parietal lobule and inferior frontal gyrus, but also in regions known to be important for higher-level mathematical processing such as the angular gyrus and the supramarginal gyrus for arithmetic (Grabner et al., 2013; Price et al., 2013; Rivera et al., 2005; Zamarian et al., 2009). Further, because recent studies have indicated that the correlation between behavioral performance in the nonsymbolic comparison and math achievement is driven by incongruent trials (Bugden and Ansari, 2015; Fuhs and McNeil, 2013; Gilmore et al., 2013), we hypothesized that the same may be true of the neural ratio effect and math achievement.

2. Materials and methods

2.1. Participants

Participants were 12th grade students who had participated in a large scale longitudinal study (Mazzocco and Myers, 2003). A total of 43 participants took part in the fMRI experiment. Three participants were excluded due to excessive head motion (>3 mm total displacement per run), one student was removed due to low performance in the scanner (56% accuracy rate, not different from chance), and one participant's data was lost due to an error in data storage. Two additional students with PSAT math scores more than 1.5 standard deviation below the national mean (<7th percentile) were removed from the sample. This criteria has previously been used to classify individuals as having math learning disability and has been linked to atypical neurobiological development of number processing mechanisms (Kovas et al., 2009; Price et al., 2007). The final imaging sample thus included 36 individuals (14 females; mean age = 17.99 years, range = 17.36–18.79 years). FMRI task analyses include the entire 36-participant sample. For two individuals, Grade 10 PSAT tests scores were not available and standard scores were prorated from 9th grade (n = 1) and 11th grade (n = 1) based on percentile rank. For three additional individuals, PSAT scores were not available at any time and thus were excluded from the PSAT analysis. They were not excluded from the first portion of our analyses because earlier standardized math measures indicated they were in the typically developing range. Thus, the remaining sample for the PSAT analysis (n = 33) represents a wide range of typically developing individuals (PSAT math mean percentile rank = 72nd, range = 22–99; PSAT reading mean percentile rank = 62nd, range = 12–99). Little's multivariate test for data missing completely at random (MCAR) indicated that there were not systematic differences according to gender or performance on the nonsymbolic comparison task (RT & accuracy) in groups with or without PSAT scores (Little's MCAR test, chi-square = 2.08, $p = 0.556$).

2.2. Tasks

Multiple tasks were performed during one scanning session including arithmetic verification, digit-matching, and non-symbolic number comparison (results from the arithmetic verification and digit matching paradigms are reported in Price et al., 2013). Only the results of the nonsymbolic number comparison task are analyzed and reported in this study.

2.2.1. Nonsymbolic number comparison

The non-symbolic comparison paradigm used in the present study was based on that reported by Halberda et al. (2008). Participants were presented with a single array of blue and yellow dots in intermixed locations (Fig. 1) and required to select, via button press, whether there were more blue or more yellow dots in the array. Trials varied according to the ratio between the dot sets (ratio calculated as the larger number divided by the smaller number, so that in a trial with 17 yellow dots and 13 blue dots, the ratio was 1.308). A total of 160 trials was presented across two runs, with the number of dots per color ranging from 5 to 21, and ratios ranging from 1.182 to 4.2. For behavioral and fMRI analyses, trials were categorized by ratio into 4 ratio bins (mean ratios = 1.21, 1.32, 1.99, 3.21) to ensure each ratio was represented by the same number of trials. Ranges for each bin were 1.18–1.25, 1.3–1.322, 1.67–2.38, and 2.6–4.2 respectively. Each bin had 40 trials and the mean ratio of each bin was used for analyses. In half the trials, the yellow dots were more numerous, and in the other half the blue dots were more numerous. Trial presentation order was randomized with respect to ratio, but fixed across participants. Stimuli were presented for 500 ms, with average inter-stimulus interval (ISI) of 6s. ISIs were varied between trials to improve deconvolution of the hemodynamic response function (HRF). Thus, an ISI could be 4, 5, 6, 7 or 8s with a mean ISI across the run of 6s. ISI length and ratio were balanced such that no ISI length was more frequently associated with a given trial type. Following the method described by Halberda et al. (2008) to limit the influence of non-numerical continuous visual parameters, the following controls were utilized. For each ratio, half the trials were dot-size controlled, meaning that the size of the average blue dot was equal to the size of the average yellow dot. On these trials, the set with more dots necessarily also had a larger total area on the screen, thus surface area was visually congruent with the more numerous dot set (Fig. 1A). The other half of the trials were area controlled, meaning that the total number of pixels for blue and yellow dots was equal, resulting in an equivalent total surface area for both sets of dots, and thus the surface area was not visually congruent with the more numerous dot set and the more numerous dot set had a smaller average dot size. These trials are referred to as incongruent (Fig. 1B).

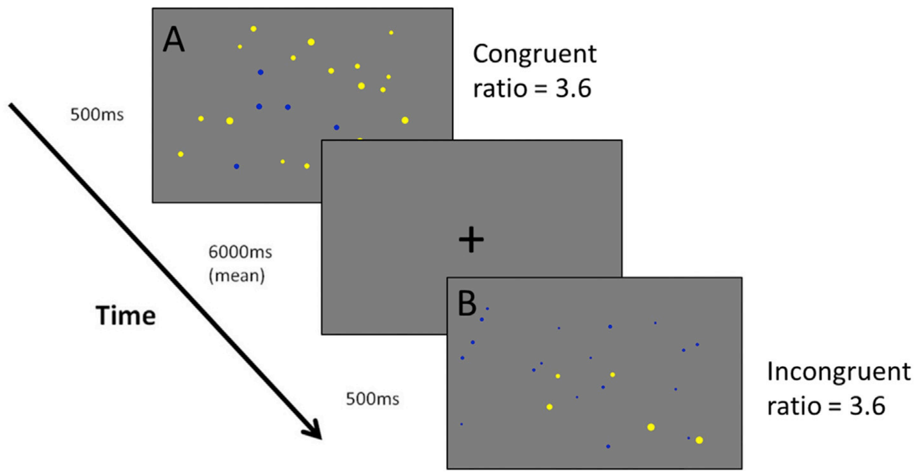

Fig. 1. Nonsymbolic numerical magnitude comparison stimuli and paradigm timing. (A) Incongruent trial example of ratio 3.6 (larger number dot set/smaller number dot set, 18/5 = 3.6). (B) Congruent trial example, also of ratio 3.6.

2.2.2. *Preliminary scholastic aptitude test (PSAT)*

As our measure of mathematical competence, we used standard scores from the PSAT math subtest sat during grade 10. The PSAT math subtest is part of a nationally administered test taken by over 3.5 million high school students in the USA each year as reported by "College Board" ("College Board," 2017). It is designed to reliably predict college entrance exam scores and serves as the qualifying test for the U.S. Merit-Based Scholarship Program, and it is thus also known at the National Merit Scholarship Qualifying Test (PSAT/NMSQT). Therefore, performance on the PSAT is highly relevant to higher education success among students in the U.S. Most individuals who take the PSAT are 10th graders, and in most states (including Maryland, where most of the participants resided) 10th graders are enrolled in a mathematics course. Beginning in 11th grade, some students choose not to pursue elective coursework (Updegraff, Eccles, Barber, & O'brien, 1996). Thus, 10th grade PSAT math subtest was chosen as a measure of broad achievement outcomes at the latest school grade during which all participants were receiving ongoing math instruction.

The PSAT math subtest contains 38 items, including word problems, geometry, algebraic equations, and complex arithmetic (no single-digit simple calculations), and it therefore represents a broad test of mathematical competence of significant importance to an individual's academic success. As a control measure for broad academic achievement, we used standard scores from the Grade 10 PSAT critical reading subtest. The PSAT reading subtest includes reading comprehension, questions about full-length and paragraph-length passages, such as speculating on the origin of the passage, as well as questions requiring students to fill in missing words from a range of sentences. Standard scores were used for all analyses, but percentile ranks are reported to characterize the sample since they are more readily interpretable. PSAT math and reading scores were correlated at $r\,(31) = 0.54$ ($p = 0.001$, n = 33).

2.3. *MRI acquisition parameters*

All MR imaging was acquired with a 3T Phillips MRI scanner using an 8-channel head coil with parallel imaging capability. Using multi-slice 2D SENSE T2* gradient-echo, echo planar imaging (EPI) pulse sequence, functional images were obtained in the axial plane. Higher order shimming was applied to the static magnetic field (B0). The EPI parameters were as follows: echo time, 30 ms; TR, 2000 ms; flip angle, 75°; acquisition matrix, 80 X 80 voxels; field of view, 240 mm; SENSE factor of 2. This protocol acquired 34 axial brain slices per TR (3 mm thickness with 1 mm slice gap, achieving a resolution of 3 mm isotropic) and a time course of 176 temporal whole brain image volumes after discarding the first five volumes to ensure steady state. Anatomical scan parameters were performed using an 8-channel head coil, 240 mm field of view, and a 1 mm isotropic MP-RAGE (magnetization-prepared rapid acquisition with gradient echo), which takes 6 min with SENSE factor 2.

2.4. *fMRI analyses*

Images were analyzed using Brainvoyager QX 2.8 (Goebel et al., 2006). Functional images were corrected for differences in slice time acquisition, head motion, and linear trends, spatially smoothed with a 6 mm FWHM Gaussian kernel, and aligned to T1 structural images, manually fine-tuned and then transformed into Talairach space (Talairach and Tournoux, 1988). Functional data were analyzed using a random effects general linear model covering the whole brain and corrected for serial correlations using the AR(2) model implemented in BrainVoyager. Analyses were masked based on a group-level anatomical image to include all cortical grey matter (including the cerebellum), excluding white matter, ventricles, subcortical, and midbrain structures, as the theoretical focus of the current analysis was limited to cortical structures directly related to higher level semantic/representational processing and to reduce the number voxel-wise comparisons not relevant for the current level of analysis. Experimental events were convolved with a standard two-gamma HRF to model the expected BOLD signal (Friston et al., 1998) corresponding to regressors of interest. All analyses were run as whole-brain contrasts modeling correct trials from each of the 4 ratio bins. Baseline was modeled as fixation time between trials. Incorrect trials were modeled as separate predictors and excluded from further analyses. Additionally, a parametric regressor was created to model the relationship between ratio and BOLD response by weighting trials with the log-transformed ratio values (i.e. the neural ratio effect). Log-transformed ratio weights were utilized because previous studies of nonsymbolic number paradigms indicate that both behavioral responses (i.e. response time and accuracy rates) and fMRI % signal change in number-sensitive regions of the brain display a relationship to numerical ratio that is logarithmically compressed (Halberda et al., 2008; Jacob and Nieder, 2009; Piazza et al., 2004). Non-transformed ratios accounted for 49% of the variance in accuracy rates and 22% of the variance in response times in the current data. Log-transformed ratios predicted 55% and 25% respectively. Further, using log-transformed ratio predictors, residual standard errors of each model decreased from 0.57 to 0.26 for accuracy rates and from 0.70 to 0.34 for response times, indicating an overall improvement in the model fits for task behaviors. Parametric weights were de-meaned in order to orthogonalize regressors in the GLM and avoid multi-collinearity since main effects and parametric effects are inherently related. A negative relationship was modeled between ratio and BOLD activity because previous research indicates that brain regions processing numerical information increase in activity with ratios that are closer together (i.e. more difficult to compare). In this study, ratio is calculated as $ratio = larger\ number/smaller\ number$. Therefore, the smaller ratio trials are generally more difficult and are expected to elicit a greater BOLD response. Modeled linearly, we expected a negative parametric relationship between ratio and BOLD response in several brain regions and thus reverse-coded the results such that a ratio effect in the expected direction (i.e. greater activity with more difficult ratios being compared) would result in a positive β-weight and thus a positive t-statistic would indicate a better fit for the expected ratio effect. This reverse-coding practice was utilized for all results associated with the parametric regressor in the current study. All statistical results were thresholded at $p < 0.005$ and corrected for multiple comparisons at $p < 0.05$ 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 1000 trials. Anatomical labels of results were defined by manually entering MNI converted peak coordinates into Jülich atlas' probability maps within the Anatomy Toolbox v2.0 in SPM8 (Eickhoff et al., 2005) and using the Talairach Daemon (Lancaster et al., 1997, 2000), prioritizing the method that allowed for greater specificity of anatomical label.

2.4.1. Nonsymbolic number comparison and the effect of congruency

To investigate differences in neural activity during nonsymbolic numerical comparison related to visual control conditions (i.e. congruent vs. incongruent), we first tested for a ratio effect across the whole-brain by performing a conjunction of random effects analysis of (a) a main effect of task vs. baseline and (b) a ratio effect (using the parametrically modeled ratio effect regressor). The conjunction revealed regions in which task-related activity was above baseline, but also increased proportional to the ratio-related difficulty of the trials (i.e. the ratio effect). Beta weights, separated by congruency condition, were then extracted from regions showing significant ratio effects and compared using within-subject t-tests to assess whether ratio-dependent activity within these regions differed according to congruency condition. A second, whole-brain random effects analysis was conducted directly comparing the parametric ratio effect between congruency conditions to reveal differential ratio effects that may not have shown a parametric ratio effect averaged across all task trials, but only within a congruency condition. Third, we investigated differences in activation according to congruency condition by contrasting congruent trials and incongruent trials irrespective of a ratio effect by performing a conjunction of random effects analysis of (a) a main effect of task vs. baseline and (b) a main effect of congruency (i.e. congruent > incongruent).

2.4.2. The neural ratio effect and math achievement

To assess the relation between the neural mechanisms underlying numerical magnitude processing and math achievement, we extracted mean beta weights of the ratio effect from clusters resulting from the previous conjunction of (a) a main effect of task vs. baseline and (b) a ratio effect and correlated participant beta weights with PSAT math scores. A subsequent correlation between the parametric ratio regressor and PSAT math scores was run at the whole-brain level to test for correlations that did not satisfy the conditions of the conjunction. It is possible that, in areas of the brain other than the four clusters resulting from the conjunction, some individuals demonstrated a parametric neural ratio effect and others did not, leading to null results for the conjunction, despite the presence of individual differences in beta weights potentially relevant for the correlation with math achievement. This whole-brain correlation was intended to test for individual differences in areas that were not significant for the conjunction at the group level. Subsequently, to control for domain-general academic achievement factors driving the behavioral correlation, the same analyses were repeated while controlling for reading achievement. To do this, PSAT math scores were entered into a linear regression with PSAT reading scores and the resulting unstandardized residuals were used for further analysis, thus removing variance associated with reading achievement. These scores are referred to as *residualized PSAT math scores* when utilized in an analysis and *PSAT math scores* otherwise.

2.4.3. The neural ratio effect and math achievement by congruency

To explore the relationship between the neural ratio effect and math achievement as a function of congruency condition, we ran whole-brain correlations between the parametric ratio regressor and math scores independently for each congruency condition with both PSAT math scores and residualized PSAT math scores.

3. Results

3.1. Behavioral results

The two behavioral variables of interest from the fMRI task were response time (ms) for correct responses and percent accuracy across all trials. To assess the effect of ratio on each of these variables we conducted two repeated-measures ANOVA with ratio (4 levels) and congruency (2 levels) as factors. To correct for multiple hypothesis testing, the critical p-values for each set of correlations were adjusted using the Benjamini-Hochberg's (B-H) False Discovery Rate method with $\alpha_{FDR} = 0.05$ (Benjamini and Hochberg, 1995), which provides a good balance between controlling for false positives and power for detecting weaker, but significant relationships. Raw p-values are reported, but significance is interpreted in terms of Benjamini-Hochberg corrected p-values. Results for accuracy revealed a main effect of ratio [$F(3, 105) = 208.73$, $p < 0.001$, partial-$\eta^2 = 0.856$], a main effect of congruency [$F(1, 35) = 10.33$, $p = 0.0003$, partial-$\eta^2 = 0.228$], and a ratio × congruency interaction [$F(3, 105) = 5.46$, $p = 0.002$, partial-$\eta^2 = 0.135$]. Greater ratios and congruent trials were each associated with more accurate performance (Fig. 2A). Individuals were more accurate during congruent trials only during ratio bins 1.32 [$t(35) = 3.59$, $p = 0.001$, Cohen's $d = 0.74$] and 1.99 [$t(35) = 3.60$, $p = 0.001$, Cohen's $d = 0.67$], but not during the smallest ratio bin, 1.21 [$t(35) = -0.59$, $p = 0.558$, Cohen's $d = -0.13$], or largest ratio bin, 3.21 [$t(35) = 1.64$, $p = 0.110$, Cohen's $d = 0.21$], after adjusting for multiple comparisons. Results for response time revealed a main effect of ratio [$F(3, 105) = 94.45$, $p < 0.001$, partial-$\eta^2 = 0.730$], a main effect of congruency [$F(1, 35) = 99.61$ $p < 0.001$, partial-$\eta^2 = 0.359$], and a ratio × congruency interaction [$F(3, 105) = 3.72$, $p = 0.014$, partial-$\eta^2 = 0.096$]. Response times were faster for larger ratios than smaller ratios and for congruent vs. incongruent trials (Fig. 2B). Individuals responded faster during congruent trials only during larger ratio bins 1.99 [$t(35) = 5.08$, $p < 0.001$, Cohen's $d = 0.46$] and 3.2 [$t(35) = 4.45$, $p < 0.001$, Cohen's $d = 0.84$], but not during the smallest ratio bins, 1.21 [$t(35) = 0.47$, $p = 0.558$, Cohen's $d = 0.05$] and 1.32 [$t(35) = 1.01$, $p = 0.320$ Cohen's $d = 0.09$], after adjusting for multiple comparisons.

To assess the relation between number comparison performance and math competence, we correlated PSAT math scores and residualized PSAT math scores with mean accuracy and response time, as well as the slopes of accuracy and response time by ratio. Mean accuracy rate did not correlate with PSAT math [$r(31) = 0.18$, $p = 0.524$]. When split by congruency condition, mean accuracy on congruent trials was not correlated with PSAT math [$r(31) = 0.11$, $p = 0.524$] nor was mean accuracy for incongruent trials [$r(31) = 0.18$, $p = 0.321$]. Mean accuracy rate did not correlate with residualized PSAT math scores [$r(31) = 0.07$, $p = 0.711$], nor did the accuracy rate for congruent [$r(31) = -0.06$, $p = 0.739$] or incongruent trials [$r(31) = 0.16$, $p = 0.374$]. Mean response time did not correlate with PSAT math across all trials [$r(31) = -0.35$, $p = 0.049$], during congruent trials [$r(31) = -0.35$, $p = 0.048$], or incongruent trials [$r(31) = -0.34$, $p = 0.056$], after correcting for multiple comparisons, though the effect size was very similar to previously reported effect sizes from meta-analyses (Chen and Li, 2014; Schneider

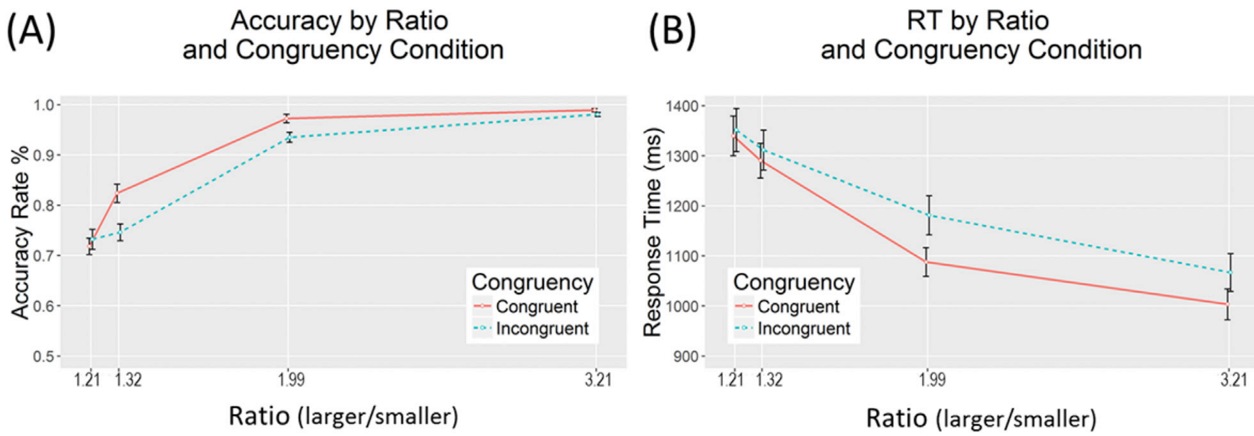

Fig. 2. Nonsymbolic comparison behavioral data from fMRI task showing (A) accuracy rate (total % correct) split by congruency condition (B) and response time (RT) split by congruency condition, by ratio.

et al., 2017). Mean response times correlated with residualized PSAT math scores across all trials [$r(31) = -0.48$ ($p = 0.005$)], congruent trials [$r(31) = -0.49$, $p = 0.001$], and incongruent trials [$r(31) = -0.46$, $p = 0.008$] after controlling for multiple comparisons, indicating that slower response time overall, and within congruency conditions, was correlated with lower PSAT math scores after controlling for PSAT reading. The slopes for mean accuracy and reaction time did not correlate with either PSAT math or residualized PSAT math scores (all *p*-values's > 0.11).

3.2. fMRI results

3.2.1. Nonsymbolic number comparison and the effect of congruency

The conjunction of the main effect of task and parametric effect of ratio revealed four clusters that showed a parametric increase with increasingly difficult ratios, including the anterior cingulate cortex (ACC) extending into the supplementary motor area (SMA), the left precentral gyrus, the left intraparietal sulcus (hIP1), and a superior/medial portion of the right superior parietal lobule (SPL) with peak activation in the precuneus, which sits superior and medial to the IPS (Fig. 3, Table 1). A comparison of the mean beta weights for the parametric ratio predictor extracted from these four regions did not show any differences according to congruency condition (results of all within-sample t-tests $p > 0.258$), indicating that in areas demonstrating a ratio effect at the whole-brain level, the ratio effect did not differ as a function of congruency condition. It is possible, however, that areas of the brain in which the parametric ratio effect was significant in only the congruent or incongruent visual control condition were not revealed when the neural ratio effect was modeled as an average of the two conditions. Therefore, we directly contrasted the parametric effect of ratio between the two congruency conditions at the whole-brain level. Results revealed that there were no brain regions showing a significant difference between the congruent and incongruent ratio effects.

Table 1
Significant clusters for conjunction of task effect (main effect) and parametric ratio effect.

Cluster	Peak TAL (x y z)	Voxels	Peak t	BA	Anatomical Description
A	(−2 8 49)	4210	5.94	32	L/R Anterior Cingulate
B	(−24 −10 52)	619	5.08	6	L Precentral Gyrus
C	(−39 −37 34)	663	4.84	40	L Intraparietal Sulcus (hIP1)
D	(18 −67 40)	836	4.42	7	R Superior Parietal Lobule (Precuneus)

Note. $n = 36$. All results cluster corrected at $p < 0.05$, uncorrected $p < 0.005$ (clusters > 391 voxels, 1 mm iso). TAL = talairach coordinates; BA = Brodmann area.

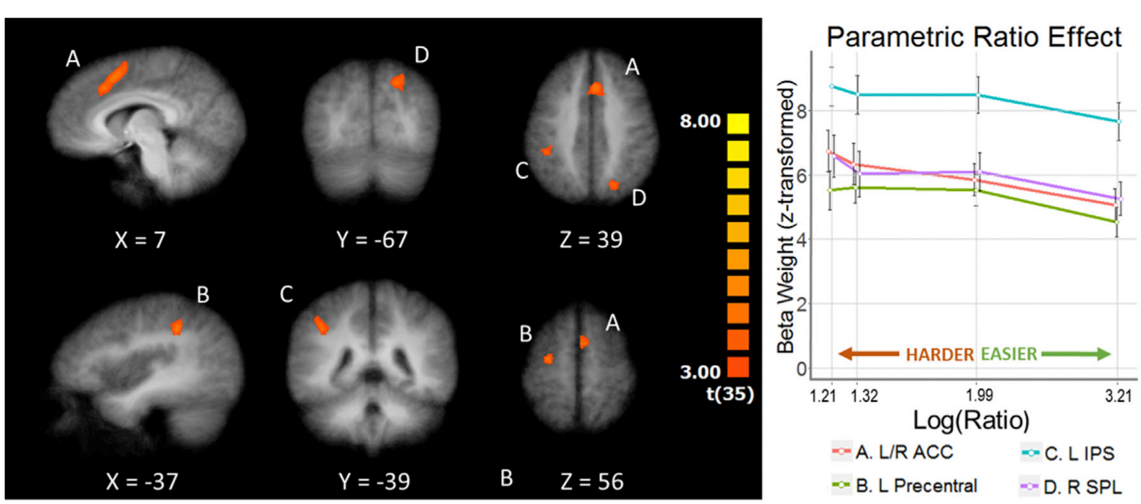

Fig. 3. Results from the whole brain conjunction analysis of main effect of task and ratio effect. Analysis was performed on de-meaned ratios but is presented here as above baseline for visualization purposes. Slices labeled in Talairach space. Lettered labels of clusters correspond to beta weight plots in line graph and Table 1. Images are presented in neurological convention, whereby right is right.

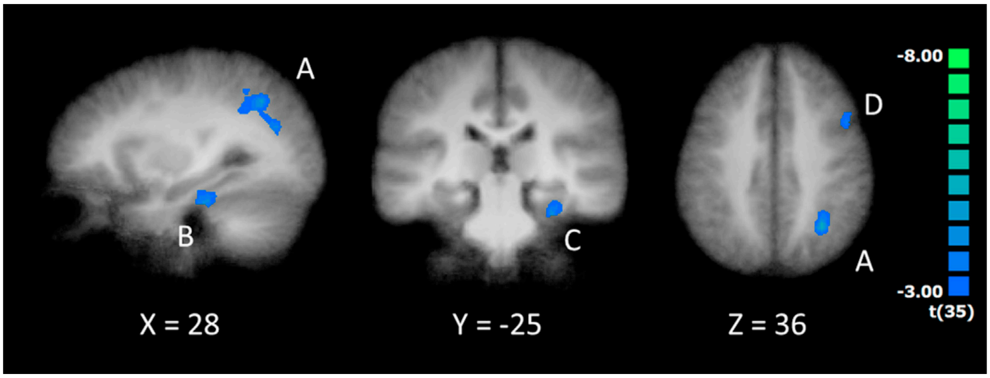

Fig. 4. Results from the whole brain conjunction analysis of main effect of task and a main effect of congruency condition. Negative t-statistics indicate BOLD response for incongruent trials is greater than for congruent trials. Slices labeled in Talairach space. Lettered labels of clusters correspond to Table 3. Images are presented in neurological convention, whereby right is right.

Table 2
Significant clusters for conjunction analysis of main effect of task and a main effect of congruency condition.

Cluster	Peak TAL (x y z)	Voxels	Peak t	CON β	CON se	INC β	INC se	BA	Anatomical Description
A	(30 −67 22)	1621	6.24	7.62	0.23	8.32	0.23	39	R Angular Gyrus
B	(51 −46 −8)	1250	4.80	3.62	0.24	4.58	0.24	37	R Fusiform Gyrus
C	(27 −25 −20)	708	4.60	3.09	0.27	3.98	0.27	35	R Parahippocampal Gyrus
D	(45 14 31)	864	4.29	3.50	0.23	4.31	0.23	9	R Inferior Frontal Gyrus

*All results cluster corrected at $p < 0.05$, uncorrected $p < 0.005$ (clusters > 339 voxels, 1 mm iso). TAL = talairach coordinates; CON = congruent; INC = incongruent; BA = Brodmann area.

The comparison of overall activation (i.e. main effects as opposed to ratio effects) between congruency conditions revealed four regions where activity is greater for incongruent trials (Fig. 4, Table 2), suggesting that incongruent trials generally recruit more neural resources in the rAG, right inferior frontal gyrus (IFG), right fusiform gyrus (rFG), and right parahippocampal gyrus. No regions were more active for congruent trials.

3.2.2. The neural ratio effect and math achievement

To assess the relation between the ratio effect and math competence, we first correlated PSAT math scores and residualized PSAT math scores with the parametric ratio effect beta weights from the four regions reported in our whole-brain ratio effect analysis. These analyses revealed no significant associations. We subsequently correlated the neural ratio effect with PSAT math scores and residualized PSAT math scores across the whole brain. Before controlling for reading, this analysis revealed two significant associations in the left and right insula whereby a greater ratio effect was associated with lower math competency (Table 3). When controlling for reading, this association was present in the left insula at the same corrected threshold ($p < 0.05$) but not in the right insula.

3.2.3. The neural ratio effect and math achievement by congruency

To assess the relation between the ratio effect and math competence when congruent and incongruent trials were considered separately, independent whole-brain correlations between PSAT math scores and the ratio effect were run for each congruency condition, followed by the same analysis run with residualized scores. Before controlling for reading, the ratio effect correlated negatively with PSAT math scores in a left-lateralized portion of the insula during congruent trials (Table 3). For incongruent trials, the ratio effect was negatively correlated with PSAT math in the left precuneus, right insula, and the right culmen of the cerebellum. Both of these results indicated lower PSAT math scores were associated with a greater ratio effect. When controlling for reading, residualized PSAT math scores correlated positively with the ratio effect during congruent trials in the right supramarginal gyrus extending into the superior temporal gyrus (Fig. 5, Table 3). However, during incongruent trials, residualized PSAT math scores correlated negatively with the ratio effect in the left angular gyrus extending into the superior temporal gyrus and the left precuneus extending into the posterior cingulate cortex (Fig. 6, Table 3).

4. Discussion

A growing body of recent research indicates that performance on the nonsymbolic comparison task is heavily influenced by visual control parameters such that the relationship between math achievement and

Table 3
Clusters showing a significant correlation between the ratio effect and PSAT math scores or residualized PSAT math scores.

Condition	Math	Peak TAL (x y z)	Voxels	Peak r	Mean r	BA	Anatomical Description
CON & INC	PSAT math	(45 8 1)	392	−0.59	−0.51	13	R Insula
		(−42 −7 1)	1924	−0.78	−0.56	13	L Insula
CON & INC	res. PSAT math	(−42 −7 4)	608	−0.62	−0.54	13	L Insula
CON	PSAT math	(−45 −1 7)	917	−0.61	−0.52	13	L Insula
INC	PSAT math	(−12 −52 43)	769	−0.65	−0.53	7	L Precuneus
		(45 8 10)	454	−0.62	−0.52	44	R Insula
		(−27 −52 −26)	421	−0.62	−0.51	–	L Cerebellum, Culmen
CON	res. PSAT math	(54 −37 19)	649	0.60	0.51	40, 22	R SMG/STG
INC	res. PSAT math	(−60 −37 22)	1548	−0.61	−0.51	39, 22	L AG/STG
		(−9 −49 40)	1101	−0.67	−0.53	7, 31	L Precuneus/Posterior Cingulate

Note. $n = 33$. All results cluster corrected at $p < 0.05$, uncorrected $p < 0.005$. TAL = talairach coordinates; CON = congruent; INC = incongruent; BA = Brodmann area; R = right; L = Left; SMG = supramarginal gyrus; STG = superior temporal gyrus; AG = angular gyrus; *res.* = residualized.

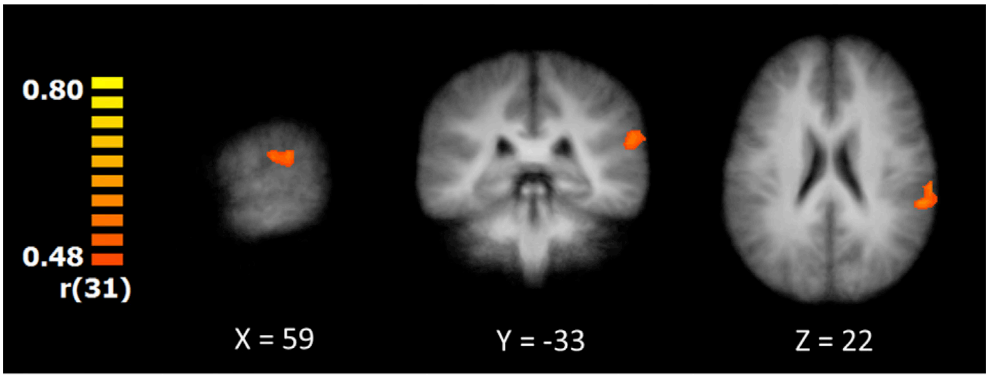

Fig. 5. Supramarginal gyrus/superior temporal gyrus cluster resulting from whole-brain correlation with residualized PSAT math scores for congruent trials. Images are presented in neurological convention, whereby right is right.

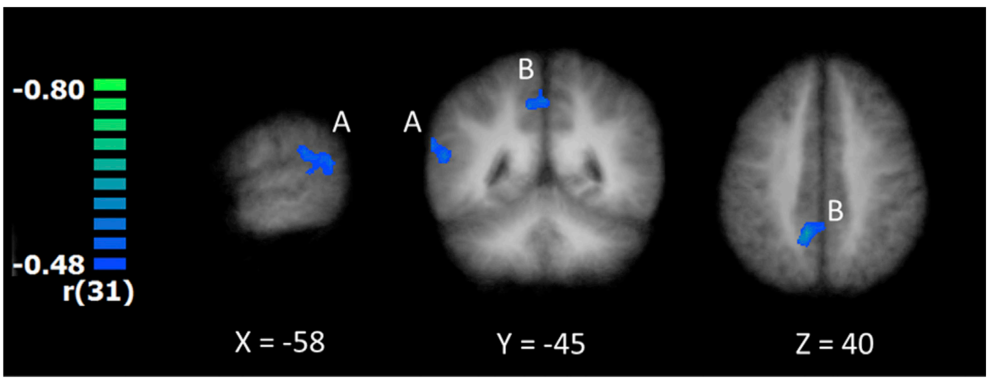

Fig. 6. (Left) (A) Left angular gyrus/superior temporal gyrus and (B) left precuneus/posterior cingulate cluster resulting from whole-brain correlation with residualized PSAT math scores for incongruent trials. Images are presented in neurological convention, whereby right is right.

nonsymbolic comparison is driven by performance on trials with incongruent visual cues in preschoolers (Fuhs and McNeil, 2013), children in primary school (Gilmore et al., 2013), and in individuals with dyscalculia (Bugden and Ansari, 2015). Further, the one neuroimaging study to investigate this issue thus far indicates that recruitment of neural resources also differs as a function of congruency condition (Leibovich et al., 2015). This earlier work suggests that the relation between nonsymbolic comparison performance and math achievement may not be driven solely by domain-specific numerical processing mechanisms. Furthermore, only a handful of neuroimaging studies have demonstrated a link between BOLD activation during nonsymbolic number processing and math achievement, and almost exclusively by way of comparison between typically developing and dyscalculic populations (Dinkel et al., 2013; Kovas et al., 2009; Kucian et al., 2011; Moeller et al., 2009; Price et al., 2007). Among those studies, there is little consensus about which cognitive mechanisms drive the relationship between the neural system used to encode numerical magnitudes (i.e. the ANS) and math skills. Only one study to date has investigated this question in a typically developing population with nonsymbolic stimuli (Gullick et al., 2011). That study did not, however, examine the influence of non-numerical visual control parameters on the observed relation. Thus, the question of whether the neural correlates of nonsymbolic magnitude processing and their relation to math competency are influenced by visual parameters in a manner similar to recent behavioral studies remains open. The present study is the first to empirically investigate this question.

Our results indicate that BOLD response was modulated by ratio in brain regions previously shown to exhibit a neural ratio effect when calculated from the average of congruent and incongruent trials, as it is in most studies, and that the ratio effect within those regions did not differ as a function of congruency condition. In other words, the effect was not driven by either condition. Further confirmation that regions of the brain sensitive to changes in numerical magnitude did not differ as a function of congruency came from the whole-brain direct contrast of the incongruent and congruent ratio effects, which did not reveal any regions that differed. This lends support to the idea that regions of the brain previously found to encode numerical magnitude, such as the IPS and SPL, do so consistently when other visual cues are congruent or incongruent with judgement about numerical magnitudes. In other words, the ratio-dependent activation during nonsymbolic number comparison does not appear to be the product of cognitive processes specific to either congruent or incongruent task conditions. In contrast, there were significant differences in overall task-related activation according to congruency condition when compared at the whole-brain level in fronto-parietal areas known to be important for encoding numerical magnitude and other mathematical computations. The neural ratio effect correlated with PSAT math in the left insula before and after controlling for reading achievement. When the relationship between the neural ratio effect and PSAT math scores was investigated independently for congruent and incongruent trials separately, results indicated a left-lateralized correlation in the insula during congruent trials and right-lateralized correlation in the insula during incongruent trials. The whole-brain correlation controlling for reading, and thus specific to math, resulted in correlations that were again in opposite hemispheres, but also opposite in the directionality of their relationship to math.

The first steps in our analysis largely confirmed previous results of nonsymbolic number tasks. Our findings of a neural ratio effect in several frontal and parietal regions replicates existing evidence from fMRI studies showing increased activity with increasingly difficult magnitude comparisons (Ansari and Dhital, 2006; Gullick et al., 2011; Price et al., 2007), and is in line with the results of previous meta-analyses showing nonsymbolic number processing is subserved by the intraparietal sulcus and regions extending into superior parietal lobule (Arsalidou and

Taylor, 2011; Sokolowski et al., 2016). The increase in activity of the anterior cingulate cortex and supplementary motor areas are likely a result of increasing task difficulty that covaries with ratio, as this trend is a frequently observed consequence of increased cognitive demand across a wide range of tasks (for a review, see Paus, 2001). In contrast, the same pattern of activity in the right superior parietal lobules (SPL) and the anterior portion of the left IPS (hIP1) are likely to represent the encoding of numerical information. Electrocorticography studies of both experimental and naturalistic settings (Daitch et al., 2016; Dastjerdi et al., 2013), fMRI adaptation studies of numeric versus non-numeric stimuli (Cantlon et al., 2006; Piazza et al., 2004) and multi-modal numerical stimuli (Vogel et al., 2017), neurological case studies of superior parietal lesions (McCloskey, 1992; Takayama et al., 1994), and other fMRI studies demonstrating numerical ratio effects (Gullick et al., 2011; Vogel et al., 2015) all indicate that a bilateral region extending from the IPS to the superior parietal lobule is involved in numerical magnitude processing. There is considerable variability in the literature in regards to the anatomical labeling of the IPS, likely due to the fact that the shape of the IPS varies greatly among individuals and that it is a large structure that extends from the occipital lobe to the postcentral sulcus. Despite this variability, the lIPS (hIPS) and rSPL structures from the current results overlap with regions identified in a large meta-analysis of number-related fMRI studies (Sokolowski et al., 2016), indicating their likely involvement in magnitude-related processing. However, the increase in parietal activation may also reflect a response to the increased attention demands of more difficult trials. Several studies show that numerical magnitude encoding, visuo-spatial attention, and working memory function converge in the superior parietal lobe (Dumontheil and Klingberg, 2012; Zago et al., 2008; Zago and Tzourio-Mazoyer, 2002). Given the limited degree of control over visual factors in stimulus design and the degree of anatomical overlap in attentional mechanisms in the parietal lobe, future studies should utilize multivariate techniques together with analyses of nuanced visual parameters in order to further investigate whether there are indeed differences not captured by the current analysis.

Comparison of task-related, non-ratio-specific neural response according to congruency condition revealed four regions that were more active for incongruent than congruent trials, including the rAG, rFG, rIFG, and right parahippocampal gyrus. By nature of the contrast, the same ratios are involved in congruent and incongruent trials, and therefore necessarily reflect differences in neural recruitment that are not dependent on the dimension of numerical magnitude. Nonetheless, several of these regions have been frequently implicated in research of numerical magnitude encoding and magnitude processing. The IFG is thought to work with parietal regions to encode numerical magnitude but has been shown to respond differentially under various working memory and inhibitory control demands (Dumontheil and Klingberg, 2012; Eiselt and Nieder, 2013). With single-cell recordings in primates, Jacob and Nieder (2014) showed that the lateral prefrontal cortex, a potential homologue of the IFG and MFG in humans, was a selection stage for goal-directed number processing that represented behaviorally relevant as well as transiently irrelevant numerical information, whereas distractor-resistant working memory representations were maintained in the parietal cortex. If both discrete and continuous quantity are processed in superior parietal regions, parietal magnitude neurons may rely on their connection to the IFG, which acts as part of a global neuronal workspace, to resolve competition among representations for selecting an appropriate rule-based response. Comparing competing aspects of the stimuli (i.e. numerical magnitude and visual cues) would increase both working memory and inhibitory control demands. If this is the case, it would stand to reason that the IFG would be more active during cases of conflict. The source of this same pattern of results in the AG is less clear since the AG is widely active in a variety of tasks, serving to integrate multisensory information and reorient attention to relevant information (Seghier, 2012). One possible explanation is that the AG may be involved in integrating stimulus information from the SPL and IFG/MFG, since it is known that the AG serves as a hub that connects to the SPL with the superior, middle, and inferior frontal gyri (Seghier, 2012). Similarly, as part of the orienting network (Petersen and Posner, 2012), the AG may be involved in orienting attentional resources from parietal systems involved in object size to parietal systems involved in numerical magnitude representation. Though the AG has often been implicated in arithmetic fact retrieval (Simon et al., 2002; Yang et al., 2017), this activity is usually left-lateralized and specific to symbolic representation of number (Holloway et al., 2010; Price and Ansari, 2011). Therefore, it is likely that the present right-lateralized AG finding is more related to attention than magnitude perception. Interpretation of increased activity in the right parahippocampal gyrus and rFG is more speculative, but may be related to the increased need during incongruent trials for a detailed and complete processing of the visual scene (for a review, see Aminoff et al., 2013). There is evidence that these regions are associated with processing scenes with high spatial frequency (Rajimehr et al., 2011). Given the short stimulus duration of the task and complexity of the dot arrays, participants are unlikely to foveate on each object, and processing the stimulus as a whole is necessary for a successful response. Given that the visual association between numerical quantity and many visual cues is reversed during incongruent trials, a more detail processing of visual associations is likely required. In sum, the present study provides evidence that congruent and incongruent trials differentially recruit neural resources in regions that support stimulus processing but are not directly involved in the encoding magnitudes.

A further aim of the current study was to investigate the relationship between patterns of activity associated with the processing of numerical magnitude and individual differences in math achievement. Our hypotheses were limited due to inconsistent findings in previous studies of dyscalculic populations and there being only one study of typically developing individuals. To date, two studies have found greater activation in various parietal areas for children with dyscalculia compared to controls (Dinkel et al., 2013; Kaufmann et al., 2009), two found weaker parietal activity in dyscalculic children (Kucian et al., 2006, 2011), another found no group differences in parietal regions (Kovas et al., 2009), and one study found less ratio-dependent modulation in dyscalculic individuals compared to controls (Price et al., 2007). Gullick et al. (2011) showed a negative correlation between the neural distance effect in bilateral perisylvian areas and math achievement in college-aged adults. Results from the current study revealed very similar findings to the study by Gullick et al. (2011), showing an inverse correlation between PSAT math scores and the neural ratio effect, such that individuals with a weaker ratio effect in the left insula and right insula had higher math scores. It is important to note that individual beta weights within this region ranged from negative to positive indicating that some people had greater activity for “easier” ratios and thus a negative beta or “inverse ratio effect”. It was these individuals who scored highest in math competency. Though left and right insular activity correlated with math performance, only activity in the right insula remained significant after controlling for PSAT reading. This suggests that ratio-dependent activity in the left insula did not specifically relate to math skills but reflected task-related processes relevant for domain-general academic achievement. A decrease in the neural ratio effect has been suggested to indicate an increase in task-related processing efficiency (Gullick et al., 2011). If more difficult trials elicit a higher BOLD response, then it would follow that individuals with better performance (those who found difficult trials less difficult) would not show as large of a ratio-dependent increase. The current results appear to support this interpretation, albeit in regions of the brain not typically associated with magnitude processing. Further, it should be noted that the ratio effect in areas of the brain previously associated with the encoding of numerical magnitudes did not correlate with math achievement as we hypothesized. This calls into question the idea that magnitude processing efficiency, as measured by the neural ratio effect in the parietal lobe, relates to math achievement in typically developing populations of the age of participants in the present study. Indeed, the weak relationship of the behaviors measured in the current study, r = 0.18 for accuracy rates and r = −0.35 for response times across all ratios, is supported by recent meta-analyses that estimate the strength of this behavioral relationship to be r = 0.20 and r = 0.241 (Chen and Li, 2014; Schneider et al., 2017) compared to a correlation of r = 0.302 with symbolic stimuli (Schneider et al., 2017).

As discussed, recent research has suggested that performance on incongruent trials during nonsymbolic number comparison tasks is more strongly related to math ability than performance on congruent trials. Therefore, the final aim of this study was to explore whether the relation between the neural ratio effect and math competency differed as a function of congruency condition. After controlling for general academic achievement, results revealed diverging patterns of association such that the ratio effect positively correlated with math competency in the rSMG during congruent trials (greater BOLD response for more difficult ratios correlated with higher math scores), but negatively correlated with math competency in the lAG during incongruent trials (greater BOLD response for easier ratios correlated with higher math scores). Interpretation of this finding should be tempered by the fact that these two correlations were not significant before controlling for reading. Though multicollinearity among PSAT reading and PSAT math is not a likely factor ($r = 0.54$) the relation between reading and math does factor into the relationship in the current findings and may be less generalizable than the right insula correlation, which was significant before and after controlling for reading. Increases in activity with increased trial difficulty likely reflect increased recruitment of cognitive resources for discrimination between and manipulation of numerical magnitude information that work in cooperation with brain regions that directly encode numerical magnitudes under differing congruency conditions. Increased activity of the SMG has been reported in response to magnitude perception even in the absence of response selection (Ansari et al., 2006). Further, children with dyscalculia have shown reduced modulation due to task-complexity during arithmetic problems in the SMG compared to typically developing peers (Ashkenazi et al., 2012). Therefore, this positive correlation between the ratio effect and math competency may indicate that increased recruitment of the SMG during number comparison is important for efficient processing of numerical information when multiple dimensions of magnitude are aligned with numerical magnitude. The negative correlation between math competency and the neural ratio effect in the left angular gyrus may represent a trend in the processing of numerical information, however, it may also reflect the processing of conflicting visual information. The angular gyrus is activated by a large variety of tasks with the common themes of combining and integrating information, manipulating mental representations, and reorienting attention to relevant information (Seghier, 2012). Differences in the correlation between math competency and activation according to congruency may be due to the fact that for incongruent trials, the degree of visual conflict increases as ratios become easier to compare. This feature is a product of the way visual controls and trials ratios are necessarily linked. For incongruent trials, the surface area of each dot set within a trial is matched. Therefore, a numerically larger dot set necessarily has smaller dots. For example, when comparing 18 dots and 5 dots in the incongruent condition, as exemplified in Fig. 1, dots belonging to the 18 dot set are smaller than the dots of the 5 dots set. Further, across trials, the degree of the difference in dot size covaries with ratio such that the greater the ratio is, the more visually incongruent the visual information. For example, if 40 dots is compared to 5 dots in the incongruent condition, the 40 dots would need to be even smaller than the 18 dots in Fig. 1 in order to equate surface area. Given these two examples, the second example 40 vs 5 is an easier numerical ratio to compare than 18 vs 5, but the degree of visual conflict in average dot size is more extreme. Therefore, it may be that individuals with higher math competency are appropriately engaging mechanisms in the angular gyrus to resolve conflicting visual cues as ratios get easier (i.e. but more visually incongruent).

Further, although both the left AG and right SMG have been more commonly associated with symbolic number and verbally mediated numerical information (Sokolowski et al., 2016), the current findings relating their activity during a nonsymbolic number comparison task to math competency suggests that their role is not limited to symbolic magnitude processing and requires further investigation. For example, it is well established that acquisition of exact, verbal number representation enhances acuity of nonsymbolic number representation (Piazza et al., 2013; Pica et al., 2004). And, an emerging body of literature suggests that symbolic number processing may mediate the influence of nonsymbolic magnitude processing on math development (Fazio et al., 2014; Lyons et al., 2012; Price and Fuchs, 2016). The current results demonstrating a relationship between ratio-dependent activity in the lAG and rSMG and PSAT math scores may reflect the increased relation between symbolic and verbal magnitude systems with nonsymbolic magnitude systems towards the end of math development in the current sample. However, only developmental imaging studies following the link between nonsymbolic magnitude representation and math skills over the course of acquiring symbolic math skills will be able to disentangle the feedback mechanisms responsible for such findings.

5. Future directions

Several limitations exist in the current study that should be noted. First, the current study used the most frequently utilized method for controlling for visual parameters of dot sets in order to make results relevant to an existing body of behavioral literature. However, this method of control is not ideal for the long-term project of understanding the interaction of congruency of visual parameters and perception of numerical magnitude, and their relation to math. Behavioral studies have provided in-depth analyses of more extensive visual properties of dot sets than those mentioned in the current study (Gebuis and Reynvoet, 2012; Leibovich and Henik, 2013). Though it is impossible to rid the nonsymbolic comparison task of the influence of visual cue congruency, two practices may be employed in future studies to further elucidate the nuanced effects presented by controlling congruency of stimulus properties. First, stimuli in future studies should tightly control as many visual parameters as possible, including surface area, density, convex hull, dot size, and luminance. Secondly, since degree of congruency and ratio are inherently related in the visual control method used in the present study, the two cannot be separated in any analysis. Future studies should provide the opportunity to analyze degree of congruency as ratio is held constant as well as the converse by designing stimuli with such properties.

Secondly, performance on the nonsymbolic comparison task is not related to all math measures equally. This may be true of neural correlate results as well. Meta-analyses indicate that the correlation for nonsymbolic comparison to early math abilities, such as mental arithmetic, has an effect size of $r = 0.454$ compared to an effect size of $r = 0.288$ for written arithmetic and curriculum-based measures (Schneider et al., 2017), such as the one used in the current study. Importantly, all three of the studies that show a difference between incongruent and congruent trials on the nonsymbolic comparison task and math achievement utilize measures of math mostly targeting mental arithmetic (Bugden and Ansari, 2015; Fuhs and McNeil, 2013; Gilmore et al., 2013). Given that the current task shows robust differences in neural activation according to visual control condition only for overall task activity, and not the neural ratio effect, the current preliminary findings about their relation to math achievement should not be considered conclusive and further studies are needed with a larger sample size and various measures of math achievement, including mental arithmetic. It may be the case that various aspects of mathematical competencies are differentially associated with number processing. Investigating these nuances may provide insight to the heterogeneity of individuals differences associated with math difficulties. Moreover, developmental differences are also likely, particularly as proficiency of mental calculations has a protracted and varied trajectory in the early school years.

Lastly, task difficulty has been shown to greatly influence the neuroimaging results of studies measuring individual differences in task-related competency. Often, more proficient individuals show lower task-related brain activation (Dunst et al., 2014). In the current study, where we found a negative correlation between the neural ratio effect and math achievement, accuracy rate was approximately 10 percent lower than in the studies of Ansari and Dhital (2006) (decreased ratio effect in children compared to adults) or of Price et al. (2007)(decreased rIPS modulation in dyscalculic children compared to control children). Unfortunately, difficulty and ratio are inextricably linked, making their comparison difficult. Future studies will need to explore paradigms that control for subject-level difficulty while allowing for a wide enough range in ratio to investigate both dimensions, ratio and subject-level difficulty.

6. Conclusion

In sum, the present results show that visual control parameters often utilized in the nonsymbolic comparison task, originally intended to serve as a control against non-numeric task strategies, significantly influence the degree of general task-related neural activity in multiple brain regions but do not influence neural activity modeled according to the ratio of number comparisons. There was a consistent neural ratio effect in the right superior parietal lobule and left IPS that did not differ by congruency, suggesting that parietal results from previous studies collapsing across congruent and incongruent trials likely captured activity related to numerical encoding mechanisms rather than inhibitory control. Incongruent trials elicited a greater overall response in several regions implicated in previous literature focused on magnitude perception, including the right inferior frontal gyrus. Further, response time in this task correlated with PSAT math scores while controlling for reading (but did not reach significance before controlling) as did neural activation modeled according to trial ratios. This finding aligns with previous research. Additionally, the directionality of the neural ratio effect related to higher math scores was opposite for congruent and incongruent trials when controlling for reading achievement. Together, these findings support the idea that performance on the nonsymbolic comparison task relates to math competency and that traditionally cited parietal mechanisms used for numerosity extraction do not differ as a function of congruency condition, but that congruent and incongruent trials generally recruit different neural mechanisms. Further, results from the current study show that the correlation between ratio-dependent neural activation and math achievement differs as a function of the congruency of non-numeric visual cues. This suggests that behavioral measures aimed at capturing math-relevant magnitude perception deficits should attend to, rather than simply control for, individual differences related to the influence of non-numeric visual information. Further, interventions aimed at training this approximate number system, should they prove successful, may find greater efficacy by intentionally manipulating the congruency of non-numeric visual cues.

References

Aminoff, E.M., Kveraga, K., Bar, M., 2013. The role of the parahippocampal cortex in cognition Elissa. Trends Cogn. Sci. 17 (8), 379–390.

Ansari, D., Dhital, B., 2006. Age-related changes in the activation of the intraparietal sulcus during nonsymbolic magnitude processing: an event-related functional magnetic resonance imaging study. J. Cogn. Neurosci. 18 (11), 1820–1828. http://dx.doi.org/10.1162/jocn.2006.18.11.1820.

Ansari, D., Dhital, B., Siong, S.C., 2006. Parametric effects of numerical distance on the intraparietal sulcus during passive viewing of rapid numerosity changes. Brain Res. 1067 (1), 181–188. http://dx.doi.org/10.1016/j.brainres.2005.10.083.

Arsalidou, M., Taylor, M.J., 2011. Is 2+2=4? Meta-analyses of brain areas needed for numbers and calculations. NeuroImage 54 (3), 2382–2393. http://dx.doi.org/10.1016/j.neuroimage.2010.10.009.

Ashkenazi, S., Rosenberg-Lee, M., Tenison, C., Menon, V., 2012. Weak task-related modulation and stimulus representations during arithmetic problem solving in children with developmental dyscalculia. Dev. Cogn. Neurosci. 2 (Suppl. 1), S152–S166. http://dx.doi.org/10.1016/j.dcn.2011.09.006.

Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. Roy. Stat. Soc. http://dx.doi.org/10.2307/2346101.

Bugden, S., Ansari, D., 2015. Probing the nature of deficits in the “approximate number system” in children with persistent developmental dyscalculia. Dev. Sci. 1–17. http://dx.doi.org/10.1111/desc.12324.

Bugden, S., Price, G.R., McLean, D.A., Ansari, D., 2012. The role of the left intraparietal sulcus in the relationship between symbolic number processing and children's arithmetic competence. Dev. Cogn. Neurosci. 2 (4), 448–457. http://dx.doi.org/10.1016/j.dcn.2012.04.001.

Butterworth, B., Laurillard, D., 2010. Low numeracy and dyscalculia: identification and intervention. ZDM 42 (6), 527–539. http://dx.doi.org/10.1007/s11858-010-0267-4.

Cantlon, J.F., Brannon, E.M., Carter, E.J., Pelphrey, K. a, 2006. Functional imaging of numerical processing in adults and 4-y-old children. PLoS Biol. 4 (5), 844–854. http://dx.doi.org/10.1371/journal.pbio.0040125.

Chen, Q., Li, J., 2014. Association between individual differences in non-symbolic number acuity and math performance: a meta-analysis. Acta Psychol. 148, 163–172. http://dx.doi.org/10.1016/j.actpsy.2014.01.016.

Clayton, S., Gilmore, C., 2014. Inhibition in dot comparison tasks. Zdm 1–12. http://dx.doi.org/10.1007/s11858-014-0655-2.

College Board. (2017). Retrieved January 19, 2017, from https://research.collegeboard.org/programs/psat/data/cb-jr/archived/2010.

Daitch, A.L., Foster, B.L., Schrouff, J., Rangarajan, V., Kaşikçi, I., Gattas, S., Parvizi, J., 2016. Mapping human temporal and parietal neuronal population activity and functional coupling during mathematical cognition. Proc. Natl. Acad. Sci., 201608434 http://dx.doi.org/10.1073/pnas.1608434113.

Dastjerdi, M., Ozker, M., Foster, B.L., Rangarajan, V., Parvizi, J., 2013. Numerical processing in the human parietal cortex during experimental and natural conditions. Nat. Commun. 4 (2528) http://dx.doi.org/10.1038/ncomms3528.

De Smedt, B., Gilmore, C.K., 2011. Defective number module or impaired access? Numerical magnitude processing in first graders with mathematical difficulties. J. Exp. Child Psychol. 108 (2), 278–292. http://dx.doi.org/10.1016/j.jecp.2010.09.003.

Dehaene, S., 1997. The Number Sense. Oxford University Press, Oxford.

Dehaene, S., Izard, V., Piazza, M., 2005. Control over Non-numerical Parameters in Numerosity Experiments.

Dinkel, P.J., Willmes, K., Krinzinger, H., Konrad, K., Koten, J.W., 2013. Diagnosing developmental dyscalculia on the basis of reliable single case FMRI methods: promises and limitations. PloS One 8 (12), e83722. http://dx.doi.org/10.1371/journal.pone.0083722.

Dumontheil, I., Klingberg, T., 2012. Brain activity during a visuospatial working memory task predicts arithmetical performance 2 years later. Cereb. Cortex 22 (May), 1078–1085. http://dx.doi.org/10.1093/cercor/bhr175.

Duncan, G.J., Dowsett, C.J., Claessens, A., Magnuson, K., Huston, A.C., Klebanov, P., Japel, C., 2007. School readiness and later achievement. Dev. Psychol. 43 (6), 1428–1446. http://dx.doi.org/10.1037/0012-1649.43.6.1428.

Dunst, B., Benedek, M., Jauk, E., Bergner, S., Koschutnig, K., Sommer, M., Neubauer, A.C., 2014. Neural efficiency as a function of task demands. Intelligence 42 (1), 22–30. http://dx.doi.org/10.1016/j.intell.2013.09.005.

Eickhoff, S.B., Stephan, K.E., Mohlberg, H., Grefkes, C., Fink, G.R., Amunts, K., Zilles, K., 2005. A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. NeuroImage 25 (4), 1325–1335. http://dx.doi.org/10.1016/j.neuroimage.2004.12.034. http://doi.org/.

Eiselt, A.-K., Nieder, A., 2013. Representation of abstract quantitative rules applied to spatial and numerical magnitudes in primate prefrontal cortex. J. Neurosci. 33 (17), 7526–7534. http://dx.doi.org/10.1523/JNEUROSCI.5827-12.2013. http://doi.org/.

Fazio, L.K., Bailey, D.H., Thompson, C.A., Siegler, R.S., 2014. Relations of different types of numerical magnitude representations to each other and to mathematics achievement. J. Exp. Child Psychol. 123 (1), 53–72. http://dx.doi.org/10.1016/j.jecp.2014.01.013. http://doi.org/.

Friston, K.J., Josephs, O., Rees, G., Turner, R., 1998. Nonlinear event-related responses. Magn. Reson. Med. 41–52.

Fuhs, M.W., McNeil, N.M., 2013. ANS acuity and mathematics ability in preschoolers from low-income homes: contributions of inhibitory control. Dev. Sci. 16 (1), 136–148. http://dx.doi.org/10.1111/desc.12013. http://doi.org/.

Geary, D.C., Hoard, M.K., Nugent, L., Bailey, D.H., 2013. Adolescents' functional numeracy is predicted by their school entry number system knowledge. PLoS One 8 (1). http://dx.doi.org/10.1371/journal.pone.0054651. http://doi.org/.

Gebuis, T., Reynvoet, B., 2012. Continuous visual properties explain neural responses to nonsymbolic number. Psychophysiology 49 (11), 1649–1659. http://dx.doi.org/10.1111/j.1469-8986.2012.01461.x. http://doi.org/.

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N., Inglis, M., 2013. Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. PloS One 8 (6), e67374. http://dx.doi.org/10.1371/journal.pone.0067374. http://doi.org/.

Goebel, R., Esposito, F., Formisano, E., 2006. Analysis of functional image analysis contest (FIAC) data with BrainVoyager QX: from single-subject to cortically aligned group general linear model analysis and self-organizing group independent component analysis. Hum. Brain Mapp. 27 (5), 392–401. http://dx.doi.org/10.1002/hbm.20249. http://doi.org/.

Goodman, M., Sands, A., Coley, R., 2015. America's Skills Challenge: Millennials and the Future. Retrieved from. papers2://publication/uuid/E2D8945E-D15E-4719-BFB0-DD9392524065.

Grabner, R.H., Ansari, D., Koschutnig, K., Reishofer, G., Ebner, F., 2013. The function of the left angular gyrus in mental arithmetic: evidence from the associative confusion effect. Hum. Brain Mapp. 34 (5), 1013–1024. http://dx.doi.org/10.1002/hbm.21489. http://doi.org/.

Gullick, M.M., Sprute, L.A., Temple, E., 2011. Individual differences in working memory, nonverbal IQ, and mathematics achievement and brain mechanisms associated with symbolic and nonsymbolic number processing. Learn. Individ. Differ. 21 (6), 644–654. http://dx.doi.org/10.1016/j.lindif.2010.10.003. http://doi.org/.

Halberda, J., Mazzocco, M.M.M., Feigenson, L., 2008. Individual differences in non-verbal number acuity correlate with maths achievement. Nature 455 (October), 8–11. http://dx.doi.org/10.1038/nature07246. http://doi.org/.

Holloway, I.D., Price, G.R., Ansari, D., 2010. Common and segregated neural pathways for the processing of symbolic and nonsymbolic numerical magnitude: an fMRI study. NeuroImage 49 (1), 1006–1017. http://dx.doi.org/10.1016/j.neuroimage.2009.07.071. http://doi.org/.

Jacob, S.N., Nieder, A., 2009. Tuning to non-symbolic proportions in the human frontoparietal cortex. Eur. J. Neurosci. 30 (7), 1432–1442. http://dx.doi.org/10.1111/j.1460-9568.2009.06932.x. http://doi.org/.

Jacob, S.N., Nieder, A., 2014. Complementary roles for primate frontal and parietal cortex in guarding working memory from distractor stimuli. Neuron 83 (1), 226–237. http://dx.doi.org/10.1016/j.neuron.2014.05.009. http://doi.org/.

Kaufmann, L., Vogel, S.E., Starke, M., Kremser, C., Schocke, M., Wood, G., 2009. Developmental dyscalculia: compensatory mechanisms in left intraparietal regions in response to nonsymbolic magnitudes. Behav. Brain Funct. BBF 5 (35). http://dx.doi.org/10.1186/1744-9081-5-35. http://doi.org/.

Kovas, Y., Giampietro, V., Viding, E., Ng, V., Brammer, M., Barker, G.J., Plomin, R., 2009. Brain correlates of non-symbolic numerosity estimation in low and high mathematical ability children. PLoS One 4 (2). http://dx.doi.org/10.1371/journal.pone.0004587. http://doi.org/.

Kucian, K., Loenneker, T., Dietrich, T., Dosch, M., Martin, E., von Aster, M., 2006. Impaired neural networks for approximate calculation in dyscalculic children: a functional MRI study. Behav. Brain Funct. BBF 2 (31). http://dx.doi.org/10.1186/1744-9081-2-31. http://doi.org/.

Kucian, K., Loenneker, T., Martin, E., von Aster, M., 2011. Non-symbolic numerical distance effect in children with and without developmental dyscalculia: a parametric fMRI study. Dev. Neuropsychol. 36 (February 2015), 741–762. http://dx.doi.org/10.1080/87565641.2010.549867. http://doi.org/.

Lancaster, J.L., Rainey, L.H., Summerlin, J.L., Freitas, C.S., Fox, P.T., Evans, A.C., Mazziotta, J.C., 1997. Automated labeling of the human brain: a preliminary report on the development and evaluation of a forward-transform method. Hum. Brain Mapp. 5 (4), 238–242. http://dx.doi.org/10.1002/(SICI)1097-0193(1997)5:4<238::AID-HBM6>3.0.CO;2–4. http://doi.org/.

Lancaster, J.L., Woldorff, M.G., Parsons, L.M., Liotti, M., Freitas, C.S., Rainey, L., Fox, P.T., 2000. Automated Talairach Atlas labels for functional brain mapping. Hum. Brain Mapp. 10 (3), 120–131. http://dx.doi.org/10.1002/1097-0193(200007)10:3<120::AID-HBM30>3.0.CO;2–8. http://doi.org/.

Leibovich, T., Henik, A., 2013. Magnitude processing in non-symbolic stimuli. Front. Psychol. 4 (June), 375. http://dx.doi.org/10.3389/fpsyg.2013.00375. http://doi.org/.

Leibovich, T., Vogel, S.E., Henik, A., Ansari, D., 2015. Asymmetric processing of numerical and nonnumerical magnitudes in the brain: an fMRI study. J. Cogn. Neurosci. 1–11. http://dx.doi.org/10.1162/jocn. http://doi.org/.

Lyons, I.M., Ansari, D., Beilock, S.L., 2012. Symbolic estrangement: evidence against a strong association between numerical symbols and the quantities they represent. J. Exp. Psychol. General 141 (4), 635–641. http://dx.doi.org/10.1037/a0027248. http://doi.org/.

Mazzocco, M.M.M., Feigenson, L., Halberda, J., 2011. Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). Child. Dev. 82 (4), 1224–1237. http://dx.doi.org/10.1111/j.1467-8624.2011.01608.x. http://doi.org/.

Mazzocco, M.M.M., Myers, G.F., 2003. Complexities in identifying and defining mathematics learning disability in the primary school-age years. Ann. Dyslexia. http://dx.doi.org/10.1007/s11881-003-0011-7. http://doi.org/.

McCloskey, M., 1992. Cognitive mechanisms in numerical processing: evidence from acquired dyscalculia. Cognition 44 (1–2), 107–157. http://dx.doi.org/10.1016/0010-0277(92)90052-J. http://doi.org/.

Moeller, K., Neuburger, S., Kaufmann, L., Landerl, K., Nuerk, H.C., 2009. Basic number processing deficits in developmental dyscalculia: evidence from eye tracking. Cogn. Dev. 24 (4), 371–386. http://dx.doi.org/10.1016/j.cogdev.2009.09.007. http://doi.org/.

Nieder, A., 2016. The neuronal code for number. Nat. Rev. Neurosci. Adv. http://dx.doi.org/10.1038/nrn.2016.40. http://doi.org/.

Nieder, A., Dehaene, S., 2009. Representation of number in the brain. Annu. Rev. Neurosci. 32 (1), 185–208. http://dx.doi.org/10.1146/annurev.neuro.051508.135550. http://doi.org/.

Nosworthy, N., Bugden, S., Archibald, L., Evans, B., Ansari, D., 2013. A two-minute paper-and-pencil test of symbolic and nonsymbolic numerical magnitude processing explains variability in primary school Children's arithmetic competence. PLoS One 8 (7). http://dx.doi.org/10.1371/journal.pone.0067918. http://doi.org/.

Parsons, S., Bynner, J., 2005. Does Numeracy Matter More? NRDC (National Research and Development Centre for adult literacy and numeracy).[aRCK], London.

Paus, T., 2001. Primate anterior cingulate cortex: where motor control, drive and cognition interface. Nat. Rev. Neurosci. 2 (6), 417–424. http://dx.doi.org/10.1038/35077500. http://doi.org/.

Petersen, S., Posner, M., 2012. The attention system of the human brain: 20 Years after. Annu. Rev. Neurosci. 21 (35), 73–89. http://dx.doi.org/10.1146/annurev-neuro-062111-150525. http://doi.org/.

Piazza, M., Facoetti, A., Trussardi, A.N., Berteletti, I., Conte, S., Lucangeli, D., Zorzi, M., 2010. Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. Cognition 116 (1), 33–41. http://dx.doi.org/10.1016/j.cognition.2010.03.012. http://doi.org/.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., Dehaene, S., 2004. Tuning curves for approximate numerosity in the human intraparietal sulcus. Neuron 44 (3), 547–555. http://dx.doi.org/10.1016/j.neuron.2004.10.014. http://doi.org/.

Piazza, M., Pica, P., Izard, V., Spelke, E.S., Dehaene, S., 2013. Education enhances the acuity of the nonverbal approximate number system. Psychol. Sci. 24 (6), 1037–1043. http://dx.doi.org/10.1177/0956797612464057. http://doi.org/.

Pica, P., Lemer, C., Izard, V., Dehaene, S., 2004. Exact and approximate arithmetic in an Amazonian indigene group. Sci. (New York, N.Y.) 306 (5695), 499–503. http://dx.doi.org/10.1126/science.1102085. http://doi.org/.

Price, G.R., Ansari, D., 2011. Symbol processing in the left angular gyrus: evidence from passive perception of digits. NeuroImage 57 (3), 1205–1211. http://dx.doi.org/10.1016/j.neuroimage.2011.05.035. http://doi.org/.

Price, G.R., Fuchs, L.S., 2016. The mediating relation between symbolic and nonsymbolic foundations of math competence. PLoS One 11 (2), e0148981. http://dx.doi.org/10.1371/journal.pone.0148981. http://doi.org/.

Price, G.R., Holloway, I., Räsänen, P., Vesterinen, M., Ansari, D., 2007. Impaired parietal magnitude processing in developmental dyscalculia. Curr. Biol. 17 (24), R1042–R1043. http://dx.doi.org/10.1016/j.cub.2007.10.013. http://doi.org/.

Price, G.R., Mazzocco, M.M.M., Ansari, D., 2013. Why mental arithmetic counts: brain activation during single digit arithmetic predicts high school math scores. J. Neurosci. Off. J. Soc. Neurosci. 33 (1), 156–163. http://dx.doi.org/10.1523/JNEUROSCI.2936-12.2013. http://doi.org/.

Rajimehr, R., Devaney, K.J., Bilenko, N.Y., Young, J.C., Tootell, R.B.H., 2011. The "‘ parahippocampal place area ’" responds preferentially to high spatial frequencies in humans and monkeys. PLoS Biol. 9 (4) http://dx.doi.org/10.1371/journal.pbio.1000608. http://doi.org/.

Ritchie, S.J., Bates, T.C., 2013. Enduring links from childhood mathematics and reading achievement to adult socioeconomic status. Psychol. Sci. 24 (7), 1301–1308. http://dx.doi.org/10.1177/0956797612466268. http://doi.org/.

Rivera, S.M., Reiss, a L., Eckert, M. a, Menon, V., 2005. Developmental changes in mental arithmetic: evidence for increased functional specialization in the left inferior parietal cortex (New York, N.Y.: 1991). Cereb. Cortex 15 (11), 1779–1790. http://dx.doi.org/10.1093/cercor/bhi055. http://doi.org/.

Schneider, M., Beeres, K., Coban, L., Merz, S., Susan Schmidt, S., Stricker, J., De Smedt, B., 2017. Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: a meta-analysis. Dev. Sci. 20 (3), e12372 http://dx.doi.org/10.1111/desc.12372. http://doi.org/.

Seghier, M., 2012. The angular gyrus: multiple functions and multiple subdivisions. Neuroscience 19 (1), 43–61. http://dx.doi.org/10.1177/1073858412440596. http://doi.org/.

Simon, O., Mangin, J.F., Cohen, L., Le Bihan, D., Dehaene, S., 2002. Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. Neuron 33 (3), 475–487. http://dx.doi.org/10.1016/S0896-6273(02)00575-5. http://doi.org/.

Sokolowski, H.M., Fias, W., Mousa, A., Ansari, D., 2016. Common and distinct brain regions in both parietal and frontal cortex support symbolic and nonsymbolic number processing in humans: a functional neuroimaging meta-analysis. NeuroImage Febr. 0–1. http://dx.doi.org/10.1016/j.neuroimage.2016.10.028. http://doi.org/.

Szűcs, D., Myers, T., 2016. A critical analysis of design, facts, bias and inference in the approximate number system training literature: a systematic review. Trends Neurosci. Educ. http://dx.doi.org/10.1016/j.tine.2016.11.002. http://doi.org/.

Szűcs, D., Nobes, A., Devine, A., Gabriel, F.C., Gebuis, T., 2013. Visual stimulus parameters seriously compromise the measurement of approximate number system acuity and comparative effects between adults and children. Front. Psychol. 4 (July), 444. http://dx.doi.org/10.3389/fpsyg.2013.00444. http://doi.org/.

Takayama, Y., Sugishita, M., Akiguchi, I., Kimura, J., 1994. Isolated acalculia due to left parietal lesion. Arch. Neurol. 51 (3), 286–291. http://dx.doi.org/10.1001/archneur.1994.00540150084021. http://doi.org/.

Talairach, J., Tournoux, P., 1988. Co-planar Stereotaxic Atlas of the Human Brain. 3-Dimensional Proportional System: an Approach to Cerebral Imaging.

Updegraff, K.A., Eccles, J.S., Barber, B.L., O'brien, K.M., 1996. Course enrollment as self-regulatory behavior: who takes optional high school math courses? Learn. Individ. Differ. http://dx.doi.org/10.1016/S1041-6080(96) 90016–3. http://doi.org/.

Verguts, T., Fias, W., 2004. Representation of number in animals and humans: a neural model. J. Cogn. Neurosci. 16 (9), 1493–1504. http://dx.doi.org/10.1162/0898929042568497. http://doi.org/.

Vogel, S.E., Goffin, C., Ansari, D., 2015. Developmental specialization of the left parietal cortex for the semantic representation of Arabic numerals: an fMR-Adaptaton study. Dev. Cogn. Neurosci. 12 (2015), 61–73. http://dx.doi.org/10.1016/j.dcn.2014.12.001. http://doi.org/.

Vogel, S.E., Goffin, C., Bohnenberger, J., Koschutnig, K., Reishofer, G., Grabner, R.H., Ansari, D., 2017. Parietal adaptation to symbolic number in both the visual and auditory modality: evidence from fMRI adaptation. NeuroImage 153 (March), 16–27. http://dx.doi.org/10.1016/j.neuroimage.2017.03.048. http://doi.org/.

Yang, Y., Zhong, N., Friston, K., Imamura, K., Lu, S., Li, M., Hu, B., 2017. The functional architectures of addition and subtraction: network discovery using fMRI and DCM. Hum. Brain Mapp. 0 (January) http://dx.doi.org/10.1002/hbm.23585. http://doi.org/.

Zago, L., Petit, L., Turbelin, M.R., Andersson, F., Vigneau, M., Tzourio-Mazoyer, N., 2008. How verbal and spatial manipulation networks contribute to calculation: an fMRI

study. Neuropsychologia 46 (9), 2403–2414. http://dx.doi.org/10.1016/j.neuropsychologia.2008.03.001. http://doi.org/.
Zago, L., Tzourio-Mazoyer, N., 2002. Distinguishing visuospatial working memory and complex mental calculation areas within the parietal lobes. Neurosci. Lett. 331 (1), 45–49. http://dx.doi.org/10.1016/S0304-3940(02)00833-9. http://doi.org/.
Zamarian, L., Ischebeck, A., Delazer, M., 2009. Neuroscience of learning arithmetic-Evidence from brain imaging studies. Neurosci. Biobehav. Rev. 33 (6), 909–925. http://dx.doi.org/10.1016/j.neubiorev.2009.03.005. http://doi.org/.