RESEARCH ARTICLE

Fronto-insular-parietal network engagement underlying arithmetic word problem solving

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Abstract

Mathematical word problems are ubiquitous and standard for teaching and evaluating generalization of mathematical knowledge for real-world contexts. It is therefore concerning that the neural mechanisms of word problem solving are not well understood, as these insights represent strong potential for improving education and remediating deficits in this domain. Here, we investigate neural response to word problems via functional magnetic resonance imaging (fMRI). Healthy adults performed sentence judgment tasks on word problems that either contained one-step mathematical operations, or nonarithmetic judgments on parallel narratives without any numerical information. Behavioral results suggested that the composite efficiency measurement of combining accuracy and RT did not differ between the two problem types. Arithmetic sentence judgments elicited greater activation in the fronto-insular-parietal network including intraparietal sulcus (IPS), dorsolateral prefrontal cortex (PFC), and anterior insula (AI) than narrative sentence judgment. Narrative sentence judgments, conversely, resulted in greater activation predominantly in the left ventral PFC, angular gyrus and perisylvian cortex compared with reading arithmetic sentences. Moreover, task-dependent functional connectivity analyses showed the AI circuits were more strongly coupled with IPS during arithmetic sentence judgments than nonarithmetic sentences. Finally, activations in the IPS during arithmetic were highly correlated with out-of-scanner performance on a distinct set of problems with the same characteristics. These results show arithmetic word problem performance differences may rely more heavily on fronto-insular-parietal circuits for mathematical model building than narrative text comprehension of similar difficulty. More broadly, our study suggests that quantitative measurements of brain mechanisms can provide pivotal role for uncovering crucial arithmetic skills.

KEYWORDS

brain connectivity, fMRI, individual difference, mathematical learning, posterior parietal cortex, problem solving, word problem

1 | INTRODUCTION

Word problems, such as “John had 20 apples and gave 5 to Amy. How many apples does John have now?” are a pedagogical practice wherein problems are presented in the manner of verbal narrative rather than numerical notation (Verschaffel, Greer, & De Corte, 2000). This type of presentation is one of the most commonly used materials in school curricula for teaching students to transfer mathematical knowledge into real-world contexts (National Mathematics Advisory Panel, 2008). Despite the ubiquity of this practice, more than a quarter of students globally struggle to solve even the simplest word problems involving whole numbers (Daroczy, Wolska, Meurers, & Nuerk, 2015;

Hegarty, Mayer, & Green, 1992; Mullis, Martin, Foy, & Arora, 2012; Riley, Greeno, & Heller, 1983). This is true even when the corresponding numerical notation can be performed with alacrity (Cummins, Kintsch, Reusser, & Weimer, 1988). In addition to the reputed relation to real-world utility, word problem proficiency has also been shown to be related to subsequent success in learning higher level mathematics skills, such as algebra (National Mathematics Advisory Panel, 2008; Powell & Fuchs, 2014). Previous studies have suggested that cognitive control has large effects on word problem performance (Passolunghi & Siegel, 2001; Swanson, 1993; Swanson & Beebe-Frankenberger, 2004; Swanson, Cooney, & Brock, 1993). Critically, still very little is known about the underlying neural mechanisms

associated with word problem solving and how they drive individual differences in behavioral performance. Understanding these neural mechanisms has the potential to contribute to the enhancement of teaching methods and instruction design (Ansari, De Smedt, & Grabner, 2012). Here we employ functional magnetic resonance imaging (fMRI) of blood oxygenation level dependent (BOLD) signal to investigate neural response to arithmetic word problems in skilled adults.

In the formation of foundational cognitive skills, cognitive control processes play a crucial role, particularly in arithmetic and reading skills (Geary, 2004; Shaywitz & Shaywitz, 2008; St Clair-Thompson & Gathercole, 2006). Cognitive control refers to the top-down executive mechanisms for voluntarily allocating mental resources based on internal goals and intentions (Buckner, 2004; Miller & Cohen, 2001). The executive system comprises mental set shifting, information updating, and response inhibition functions, and has often been associated with working memory (Miyake et al., 2000). Neuroimaging studies have provided fruitful evidence that the brain responses associated with cognitive control primarily involve several nodes in the fronto-insular-parietal network, including anterior insula (AI), dorsal anterior cingulate cortex (dACC), dorsolateral prefrontal cortex (DLPFC) and the posterior parietal cortex (PPC) (Cai et al., 2015; Levy & Wagner, 2011; Miyake et al., 2000; Supekar & Menon, 2012). The AI coupling with dACC has been implicated in subjective salience of external stimuli and in contributions to complex cognitive processes including central executive function, whereas DLPFC coupling with the intraparietal sulcus (IPS) within the PPC is engaged in information retention and manipulation during working memory as well as constructing problem solutions (Levy & Wagner, 2011; Miller & Cohen, 2001; Seeley et al., 2007). Uniquely, the PPC is a highly heterogeneous structure encompassing anatomical subdivisions that appear to play differential roles in arithmetic problem solving (Caspers et al., 2006; Chang, Metcalfe, Padmanabhan, Chen, & Menon, 2016; Choi et al., 2006; Rosenberg-Lee, Chang, Young, Wu, & Menon, 2011; Wu et al., 2009). Within the structure, the IPS has been associated with representing abstract quantity information and magnitude manipulation (Ansari, 2008; Arsalidou & Taylor, 2011; Dehaene, Piazza, Pinel, & Cohen, 2003), and hence is considered as the most crucial component in mathematical cognition. Ventral and posterior to the IPS region is the angular gyrus (AG). Brain activity within the AG is associated with retrieval and manipulation of semantic knowledge (Binder, Desai, Graves, & Conant, 2009). In numerical processing, this area has been interpreted as responsible for rote verbal retrieval of problem answer facts such as a memorized multiplication table rather than procedure based subtraction solutions which are often computed discretely upon query, and exact rather than approximate calculation (Dehaene et al., 2003). In the language domain, AG is often activated during real words relative to nonwords and during semantic-related, relative to semantic-unrelated words (Binder & Desai, 2011; Fiebach, Friederici, Muller, & von Cramon, 2002). Within these fronto-insular-parietal circuits, brain signals are initiated from right AI to other nodes (Cai et al., 2015; Supekar & Menon, 2012), strongly implying that the right AI functions as the causal hub in the interconnected fronto-insular-parietal cognitive control network, and that the right AI integrates information from other subnetworks (Honey, Kötter, Breakspear, & Sporns, 2007; Uddin, Supekar, Ryali, & Menon, 2011).

The nodes within fronto-insular-parietal circuits not only exhibit engagement (Arsalidou & Taylor, 2011; Houde, Rossi, Lubin, & Joliot, 2010; Rosenberg-Lee, Chang, et al., 2011; Wu et al., 2009) but also synchronize to support the cognitive processing of numerical function and calculation (Chang, Lee, & Metcalfe, 2018; Rosenberg-Lee et al., 2015; Rosenberg-Lee, Barth, & Menon, 2011; Supekar & Menon, 2012). One piece of evidence is provided by an fMRI study which found strong functional connectivity and causal interactions between the AI, dACC, DLPFC, and PPC during simple addition problem solving; this network continued to strengthen from childhood into adulthood in concert with increased skill proficiency (Supekar & Menon, 2012). Another study demonstrated that functional coupling of fronto-parietal circuits during addition problem solving in second graders significantly increased after 1 year of schooling with mathematical curriculums (Rosenberg-Lee, Barth, et al., 2011). Even more illuminating, is the finding that functional connectivity between PPC and PFC at rest is linked with children's out-of-scanner performance measured as school arithmetic attainment (Chang et al., 2018). Despite the abundant evidence of how these neural networks substantiate numerical problem solving, critically, still very little is known about how fronto-insular-parietal networks engage and strengthen to furnish arithmetic word problem solving, a set of mathematical materials that require much more integration of context, and how the functioning of these circuits drives behavioral variability.

Behavioral studies have suggested that cognitive control plays a crucial role in arithmetic word problem solutions (Passolunghi & Siegel, 2001; Swanson, 1993; Swanson & Beebe-Frankenberger, 2004; Swanson et al., 1993). The executive functions are necessary in helping individuals to establish word problem solving strategies (Passolunghi & Siegel, 2001; Swanson & Beebe-Frankenberger, 2004). Passolunghi and Siegel found that compared with good word problem solvers, children with low word problem solving skills performed more poorly on inhibitory process and working memory assessments, such as word and digit span tasks (Passolunghi & Siegel, 2001). Furthermore, working memory measures were found to be predictive of arithmetic word problem solving achievement (Lee, Ng, Ng, & Lim, 2004; Swanson et al., 1993). In another two studies, Swanson and colleagues found that both children and adults with arithmetic learning deficits performed much more poorly on word problem solving and working memory tasks than their typically developing peers (Swanson, 1994; Swanson & Beebe-Frankenberger, 2004). In addition, direct training on arithmetic word problem solving strategy not only enhanced children's word problem skills but also efficiently transferred to gains on working memory assessments (Swanson, 2015). Collectively these studies have shown cognitive control plays a critical component in arithmetic word problem solving, perhaps by integrating information from the problem context and constructing problem representations (Swanson & Beebe-Frankenberger, 2004).

In line with the behavioral findings, the fronto-insular-parietal circuits have been consistently identified when investigating neural correlates of arithmetic word problem-solving (Lee et al., 2007; Newman, Willoughby, & Pruce, 2011; Prabhakaran, Rypma, & Gabrieli, 2001; Zhou et al., 2018). Prabhakaran et al. (2001) investigated brain responses of reading word problems involving the four basic arithmetic operations in adults. They found that increasing problem

complexity with additional arithmetic operands resulted in increased engagement of DLPFC. In another more recent study, Zarnhofer et al. (2013) compared brain responses during reading of an arithmetic word problem (e.g., *Anna goes for a walk. She walks 4 km/hr. What distance does she cover in 3 hr?*) and during a formulation problem where participants were instructed to form a mathematical model without the story context (e.g., *what result do you obtain when multiplying 3 by a factor of 4?*). They found that reading formulation problems activated brain regions associated with visual functions, such as lingual gyrus in occipital lobe, whereas word problems engaged angular gyrus as well as middle temporal gyrus, the regions that had been associated with semantic processing and integration during reading. Newman et al. (2011) examined the processing differences between problems presented as verbal narrative and numerical formats. Specifically, an example of verbal format was *"The day before my favorite day is 2 days after Thursday"* whereas the corresponding numerical problem would be $4 + 2 = x - 1$. In this study, verbal and numerical problems both activated large overlapping regions including the PPC, DLPFC, ventrolateral prefrontal cortex (VLPFC), and basal ganglia. Additionally, number problems relied more on the processing of the intraparietal sulcus (IPS), while the word problems engaged inferior frontal gyrus (IFG) within VLPFC and the pre-supplementary area (pre-SMA). Zhou and colleagues (2018) found that when solving problems involving straight description and large quantity calculation, such as *"Lucy has 146 marbles. Her brother has 68 marbles. How many marbles does she have than her brother?"*, brain responses were associated with AI and dACC. In contrast, when solving problems that required verbal reasoning and relatively small quantity manipulation, such as *"Lucy has 90 marbles. Her brother has 60 marbles. How many marbles must she give to him so both of them will have the same amount?"*, activations were found in the VLPFC, AG within the PPC, as well as middle temporal gyrus (MTG). Together, these early studies have pointed to an obligatory role of the fronto-insular-parietal engagement during the brain reacting to arithmetic word problems that require analogy of the correct mathematic model. However, all these early contributions have failed to control for problem difficulty and even visual complexity, greatly limiting the interpretation of results. Moreover, all these previous studies have focused on different perspectives of arithmetic word problem solutions. Another shortcoming in the current understanding is that it is still unknown how the fronto-insular-parietal network functions as an interconnected neural circuit to support arithmetic word problem solving. Of even greater importance than general network dynamics, is that no attempt has yet been made to examine how individual differences of arithmetic word problem solving skills are related to this neural network.

In the current study, we investigate these questions by collecting fMRI data from 26 adults who were proficient at general arithmetic problem solving skills. We manipulated the numerical component of word problems and compared brain responses between solving word problems with an embedded arithmetic operation (hereafter referred to as arithmetic word problem, AWP) and reading parallel narratives without any numerical information (hereafter referred to as nonarithmetic word problem, NWP) (see Figure 1). This manipulation allowed us to match the reading and judgment components of the two problem types such that the only difference was the need to derive a

mathematical model. To answer the AWP, participants were required to decode text, build a corresponding mathematical model, and solve the problem model by arithmetic calculation, whereas the NWP sentence judgment only required text comprehension but not calculation. The Chinese mandarin system provides suitable materials for this manipulation, because of its lack of a counting syntax (Li, Barner, & Huang, 2008). For example, for "天鹅" (pronounced as "tian-e") can mean both "swan" and "swans." Instead, the quantity properties and measuring units of the Chinese nouns are represented by classifiers (e.g., "san-zhi-tian-e" means "three swans." "zhi" is the unit for animal) (Her, 2012; Li et al., 2008). A previous neuroimaging study indicated that the process of reading Chinese numeral classifiers does not involve the same brain response profiles as judging Arabic digits and dot quantities, suggesting that quantity processing of classifiers is independent of numerical processing (Cui et al., 2013). We take this as evidence that the Chinese classifiers do not elicit automatic and explicit quantity cues when reading Chinese nouns.

Word problems including large quantity calculation are associated with AI and dACC activity, whereas problems with verbal reasoning and small quantity manipulation require language areas such as AG and MTG (Zhou et al., 2018). Furthermore, arithmetic knowledge typically activates greater levels of IPS than nonarithmetic knowledge (Amalric & Dehaene, 2016; Newman et al., 2011; Thioux, Pesenti, Costes, De Volder, & Seron, 2005). Thus, combining expectations for arithmetic and quantitatively demanding word problems, our key hypothesis was that arithmetic word problems would recruit stronger functional activations within nodes of the fronto-insular-parietal network than word problems not requiring numerical computations. Conversely, and in line with Zhou's study (Zhou et al., 2018), nonarithmetic word problems were expected to be associated with stronger activations of AG and MTG.

As functional coupling between fronto-insular-parietal nodes is strengthened during arithmetic computations (Chang et al., 2016; Rosenberg-Lee, Barth, et al., 2011; Supekar & Menon, 2012), our second hypothesis was that arithmetic word problems would engage stronger functional connectivity between fronto-insular-parietal nodes compared with nonarithmetic word problems. We also predicted functional dissociation between the two problem types within the PPC. As IPS is associated with representing abstract quantity information (Arsalidou & Taylor, 2011; Cohen Kadosh, Lammertyn, & Izard, 2008; Dehaene et al., 2003) whereas AG is associated with verbal fact retrieval (Dehaene et al., 2003; Grabner et al., 2007), we predicted that arithmetic word problems would engage higher activations in the IPS while nonarithmetic word problems would elicit increased AG activation.

Finally, we examined whether these neurofunctional characterizations are related to variability in behavioral performance as would be expected if the network differences between the two types of processing were truly related to problem solving, instead of basic semantic context effects between the two conditions. We hypothesized that individual differences in arithmetic word problem solving performance would be uniquely associated with fronto-insular-parietal activations, due to the necessity of calculation for the problem mathematic model.

FIGURE 1 Behavioral paradigm of the current study. Each trial started with a “+” fixation sign for 500 ms followed by a problem for 12 s. Each problem was orthogonally manipulated and presented as an arithmetic word problem (AWP) and as a non-arithmetic word problem (NWP). The AWP involved a two-operand addition or subtraction mathematical model whereas the NWP were composed with the same sentence structure but without an arithmetic operation embedded in the story. After the problem was presented, participants were required to indicate, via a button box, whether the description of the problem shown was correct or incorrect

2 | METHODS

2.1 | Participants

A total of 26 adults (12 males and 14 females) with the age range from 20.25 to 27.64 (Mean = 22.25, $SD = 1.90$) were recruited from local educational institutions through campus flyers in Taipei city, Taiwan. All participants were right handed with no reported history of psychiatric or neurological disorders and had normal or corrected-to-normal vision. All of the study protocols were approved by the National Chengchi University Review Board. All participants were volunteers and were treated under the guidelines of declaration of Helsinki.

2.2 | Stimuli and task

The task consisted of two conditions: arithmetic word problem (AWP) and nonarithmetic word problem (NWP). All the problems were presented as a short story and constructed in Chinese. AWP were sentences involving an addition or subtraction mathematical model, see Table 1 for examples. In one half of the addition AWP one operand was greater than 15, and were considered large. In the other half of addition AWP both of the operands were equal to or less than

15, and were considered small. The problem size of subtraction AWP was inversed with respect to the problem size of addition AWP problems. After the problem was presented, participants were required to indicate, via a button box, whether the description of the problem was shown as correct or incorrect. Incorrect answers for arithmetic word problems deviated by ± 1 or ± 2 from the correct answers. The NWP were composed of the same sentence structure but without an arithmetic operation embedded in the story (see, e.g., Table 1). Participants indicated whether the semantic descriptions were correct or incorrect. The answers were correct in 50% of the trials for both problem types. The number of characters, average frequency of each character (indexed by Academia Sinica, 2004), and average strokes did not differ between the two types of problems (all $p > 0.05$).

There were two sets of stimuli, each with 64 problems. Each stimuli set comprises 32 problems per condition, broken up into three functional runs, each with 21 or 22 trials. For the sequence that each participant underwent these three runs were counter balanced. The first set of stimuli were administered in fMRI and presented in an event-related design. Each trial started with a “+” sign as fixation for 500 ms followed by a problem for 12 s to ensure participants had sufficient time to read through each problem. Participants were

TABLE 1 Examples of AWP and NWP stimuli

Condition	Average frequency	Average # of strokes	Example sentences
AWP	6,406.40	9.75	池塘裡有/8/隻/白天鵝/和/7/隻/黑天鵝/./池塘裡有/15/隻/天鵝/。 Pond/in/have/8/ZHI/white swan/and/7/ZHI/black swan/./pond/in/have/15/ZHI/swan/. Chítáng/li/yǒu/8/zhī/bái tiān'é/hé/7/zhī/hēi tiān'é/./ chítáng/li/yǒu/15/zhī/tiān'é/.
AWP	7,104.88	8.21	小芳有/18/元/./想/買/麵包/和/豆漿/不/夠/5/元/./麵包/和/豆漿/一共/22/元/。 Xiaofang/have/18/dollar/./want/buy/bread/and/soy milk/not/enough/5/dollar/./bread/and/soy milk/in total/22/dollar/. Xiǎo fāng/yǒu/18/yuán/./xiǎng/mǎi/miànbāo/hé/dòujiāng/bù/gòu/5/yuán/./miànbāo/hé/dòujiāng/yìgòng/22/yuán/.
NWP	8,625.00	9.33	池塘裡有/白天鵝/和/黑天鵝/./池塘裡/都/是/白色/的/天鵝/。 Pond/in/have/white swan/and/black swan/./ Pond/in/all/is/white/of/swan/. Chítáng/li/yǒu/bái tiān'é/hé/hēi tiān'é/./ chítáng/li/dōu/shì/báisé/de/tiān'é/.
NWP	6,816.76	9.62	小芳有/錢/./想/買/麵包/和/豆漿/但/錢/不/夠/./小芳沒有/買到/麵包/和/豆漿/。 Xiaofang/have/money/./want/buy/bread/and/soy milk/but/money/not/enough/./ Xiaofang/not/buy/bread/and/soy milk/. Xiǎo fāng/yǒu/qián/./xiǎng/mǎi/miànbāo/hé/dòujiāng/dàn/qián/bù/gòu/./xiǎo fāng/méiyǒu/mǎi dào/miànbāo/hé/dòujiāng/.

The average of word frequency, strokes, and number of characters do not differ between AWP and NWP. AWP = arithmetic word problem; NWP = nonarithmetic word problem. “ZHI” is a Chinese classifier.

instructed to respond within 1 s after the problem presentation duration. After participants responded to the problem, another 0.75 s blank frame was presented for capturing (if any) delayed responses. Finally, the screen remained blank as jittered inter-trial interval between 2 and 5 s (Figure 1). Each run took approximately 6 min and 30 s. Because the fMRI task was designed to avoid motor responses contaminating the brain response related to solutions, as the supplementary motor area (SMA) is consistently activated during arithmetic problem solving (Menon, Cohen Kadosh, & Dowker, 2014), we conducted a parallel out-of-scanner task to derive behavioral performance using the other set of the stimuli and administered it outside the scanner after the fMRI scan. In order to obtain the actual response time, the out-of-scanner procedure was self-paced without waiting for 12 s. The out-of-scanner assessment was tested under normal situations without MRI environment and, therefore, provides more precise and replicable measurement (Mencl et al., 2000).

2.3 | fMRI data acquisition

Brain imaging data were acquired using a Siemens MAGNETOM Skyra 3 T scanner at National Chengchi University in Taipei, Taiwan. During the scan, head movement was minimized using cushions placed around the participant's head. We employed T2* weighted echoplanar sequences with the following parameters: TR = 2 s, TE = 30 ms, flip angle = 90°. The field of view was 220 × 220 mm, and the matrix size was 64 × 64, providing an in-plane spatial resolution of 3.4 mm. In the same scan session, high-resolution T1-weighted MRI sequences were acquired for each participant to aid localization of functional data. The following parameters were used: TR = 3,500 ms; TE = 3.37 ms; flip angle = 7°; 256 × 256 field of view; 192 slices in axial plane; 256 × 256 matrix, yielding acquired resolution = 1 mm.

2.4 | fMRI data preprocessing

Functional MRI data were pre-processed using SPM8 (<http://www.fil.ion.ucl.ac.uk/spm>). Prior to statistical analysis, images were corrected for errors in slice timing, realigned to the first image of each run to correct for head motion, coregistered to each of the individual participants' structural scans, normalized to standard stereotaxic space (based on the Montreal Neurologic Institute coordinate system), and smoothed with a 6 mm full-width half-maximum Gaussian kernel to decrease spatial noise. We conducted a procedure similar to AFNI 3dDespike (Cox, 1996) to correct for transient excesses in participant movement (Chang et al., 2016; Chang, Rosenberg-Lee, Metcalfe, Chen, & Menon, 2015). Deviant volumes were identified as having either scan-to-scan displacement greater than half of z voxel size (1.7 mm in this study) or change in global signal greater than 5%. The scan-to-scan displacement was computed as the square root of the sum of both translational and rotational displacement difference between two consecutive scans. Rotational displacements were converted from degrees to millimeters by assuming a brain radius of 65 mm. Deviant volumes were then interpolated using the two adjacent scans. No participants had greater than 5% of deviant volumes. The movement of the final participants range was on average of 0.32 (SD 0.17), 0.41 (SD 0.23), and 0.95 (SD 0.68) mm in the x, y, and z

direction, with 0.26 (SD 0.15), 0.70 (SD 0.39), and 0.26 (SD 0.17) degrees of roll, pitch, and yaw. The overall average of the percentage of deviant volumes was 0.63%.

2.5 | Individual and group level analysis

Statistical analysis was performed on both individual and group level data using the general linear model (GLM) implemented in SPM8. Individual subject analyses were conducted by applying GLM that modeled the correctly responded trials of AWP and NWP as two regressors and convolved with a canonical hemodynamic response function to model the expected BOLD signal. Each trial was modeled for 12 s, starting from the onset of the problem presentation. Incorrectly answered trials, the epoch participants made responses, and the 6 motion parameters generated in SPM8's realignment procedure were included as regressors of no interests. For each subject, voxel-wise *t*-statistics maps of each effect of interests were generated for each participant. We focused on the following contrasts: (1) AWP-NWP; (2) NWP-AWP. These contrast images were then analyzed in group-level one-sample *t*-tests to identify brain responses for each condition. All significant results were determined based on a voxel-wise height threshold of $p < 0.001$ and multiple comparison correction at a spatial extent threshold of FWE $p < 0.05$ after gray matter masking.

2.6 | Cytoarchitectonic probabilistic labeling of the posterior parietal cortex

To localize the brain responses in PPC, we conducted additional analyses using cytoarchitectonic probability maps to characterize and label functional activations in the PPC. These maps are based on observer-independent analyses of cytoarchitectonic organization that provide an anatomically precise and consistent basis for examining the differential profile of fMRI responses during arithmetic problem solving as demonstrated in several prior studies (Chang et al., 2015; 2016; Rosenberg-Lee, Chang, et al., 2011; Wu et al., 2009). These maps provide cytoarchitectonically distinct subdivisions of the three IPS [including hIP2 on the anterior lateral bank of the IPS, hIP1 which is posterior to hIP2 (Choi et al., 2006), and hIP3 which is posterior and medial to both hIP1 and hIP2 (Scheperjans et al., 2008)], and two AG [the anterior and posterior areas, PGa and PGp, encompassing the caudal aspects of the PPC (Caspers et al., 2006)] mappings. We evaluated these ROIs using SPM Anatomy Toolbox (Eickhoff et al., 2005). The spatial distribution of regional activations was characterized by three metrics—the probability that a peak in the cluster was assigned to a specific region, the percentage of an activation cluster that was in a specific region, and the percentage of a specific region that belonged to an activated cluster. To avoid spatial overlap in these probabilistic ROIs, each voxel was assigned to the region within which it demonstrated the highest probability. This approach yields continuous nonoverlapping parcellation of the PPC that can be used to uniquely localize regional responses.

2.7 | Brain-behavior correlations

Whole-brain regression analyses were conducted to investigate the relation between brain responses toward each type of problem and behavioral performance. Because accuracy was close to ceiling and had minimal variability, we focused on examining the correlation between response times administered outside the scanner and the contrast images between the two problem types. Group level regression analyses were used to assess the relationship between each score of AWP and NWP and the corresponding contrast images.

2.8 | Task-dependent functional connectivity analyses

Psychological physiological interaction (PPI) analysis (Friston et al., 1997) was implemented to examine task-dependent functional connectivity within the whole brain. PPI evaluates the strength of functional interactions between a given seed and other brain regions after accounting for the activation differences between two tasks. Because deriving ROIs from the same dataset may produce inflated correlations (Vul, Harris, Winkielman, & Pashler, 2009), we define the seed ROI using meta-analysis based on the approach of our previous work (Chang et al., 2018). We first performed a Bayesian meta-analysis using the search term “cognitive control” on Neurosynth (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011). This analysis generated 428 studies. In order to obtain more stringent brain maps that are relevant to cognitive control tasks, we focused on reverse inference maps which reported brain regions that are preferentially related to cognitive control. The resulting brain map encompassed the conventional nodes of fronto-insular-parietal network, including the right AI (rAI, volume size 1,016 mm³), dACC (volume size 352 mm³), right DLPFC (rDLPFC, volume size 960 mm³), right VLPFC (rVLPFC, volume size 296 mm³), and the right PPC (rPPC, volume size 736 mm³). As a dominant role of the rAI was extensively reported in previous studies and considered as the cortical hub for cognitive control (Cai et al., 2015; Sridharan, Levitin, & Menon, 2008; Supekar & Menon, 2012; Uddin et al., 2011) and the rAI was the node with both the highest peak and greatest extent in the fronto-insular-parietal nodes identified from Neurosynth, here we focused on rAI as the seed ROI. Using this

seed, our previous study had identified the strengthening of intrinsic rAI circuits was associated with arithmetic skills as well as reading comprehension (Chang et al., 2018). The time series from the seed ROI was de-convolved to uncover neuronal activity and multiplied with the task design waveforms to form an interaction term. This interaction term was convolved with the hemodynamic response function (HRF) to form the PPI regressor. Contrast images corresponding to differences in connectivity between AWP and NWP were generated for each subject and entered into subsequent within-group one-sample t-tests.

3 | RESULTS

3.1 | Behavioral performance efficiency of arithmetic and nonarithmetic word problems did not differ

Behavioral results of the in-scanner behavioral tasks are presented in Supporting Information Results, Figure S1, and Table S1. Because participants were not allowed to immediately respond after the stimuli were presented, we conducted a parallel design with a different set of stimuli using self-paced procedure and administered outside the scanner after each fMRI session (see Methods section). The correlation between in-scanner and out-of-scanner accuracy of both the problem types does not reach significance ($r = 0.211$, $p = 0.302$), because most of the participants were within the ceiling range. There was a significant correlation between the response times of in-scanner and out-of-scanner performance ($r = 0.678$, $p < 0.001$). We then examined the mean accuracy data of the out-of-scanner performance using a paired sample t-test with problem type (arithmetic, nonarithmetic) as the within-subject factor. Participants responded more accurately to arithmetic than nonarithmetic word problems (97 vs. 94%, $t [25] = 2.896$, $p = 0.008$). A parallel analysis was conducted on mean reaction time of each participant. The results did not show difference between the two problem types (4.58 vs. 4.37 s, $t [25] = 1.294$, $p = 0.207$) (Figure 2, Supporting Information Table S1). Because the accuracy and reaction time reflected reverse direction, in order to account for speed-accuracy trade off, we calculated a standardized efficiency score by

FIGURE 2 Out-of-scanner performance during arithmetic word problem (AWP) and nonarithmetic word problem (NWP) solving. Participants responded more accurately to arithmetic than nonarithmetic word problems ($p = 0.008$). Although the reaction time (RT) value of AWP is higher than NWP, this pattern does not reach significance ($p = 0.207$). To account for speed-accuracy trade off, standardized efficiency scores were calculated by averaging z-scores of accuracy and negative RT. this measurement did not show difference ($p = 0.918$). n.s. not significant.

** $p < 0.01$ [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 3 Brain regions that showed significantly different activation level between arithmetic (AWP) and non-arithmetic word problem (NWP) solving. AWP showed greater activations in distributed brain regions, including the bilateral intraparietal sulcus (IPS), middle frontal gyrus (MFG), right insula and fusiform gyrus (FG), and the left cerebellum when compared with NWP. NWP, in contrast, showed greater activations in distinct regions, including the left inferior frontal gyrus (IFG), bilateral middle (MTG) and inferior temporal gyri (ITG), and angular gyrus (AG) when compared with AWP [Color figure can be viewed at wileyonlinelibrary.com]

averaging z-scores of accuracy and negative reaction time (Chang et al., 2015; Salthouse & Hedden, 2002). The efficiency score did not show difference (-0.000 vs. -0.000 , $t[25] = 0.000$, $p = 1.000$), indicating that performance was parallel between the two problem types.

3.2 | Arithmetic word problem solving resulted in more fronto-insular-parietal activations

We focused on contrasting the images between AWP and NWP. We first examined brain regions that showed greater activation in

TABLE 2 Brain regions that showed greater activations during AWP solving compared with NWP solving

Region	BA	# of voxels	Peak T-score	MNI coordinates		
				x	y	z
AWP > NWP						
R intraparietal sulcus/	40	7,416	7.94	48	−36	54
L lateral occipital gyrus/			7.06	−24	−62	30
R lateral occipital gyrus/			6.92	30	−60	36
R fusiform gyrus/	37		6.90	44	−54	−14
R intraparietal sulcus/	39		6.76	30	−56	44
L supramarginal gyrus/	40		6.65	−52	−36	48
L intraparietal sulcus/	40		5.64	−40	−46	46
L fusiform gyrus	19		4.91	−30	−78	22
L cerebellum		717	6.81	−26	−56	−36
L middle frontal gyrus	46	288	6.25	−48	44	12
R middle frontal gyrus	10	420	5.89	44	46	12
R hippocampus	54	342	5.42	22	−38	6
R precentral gyrus/ inferior frontal gyrus/	44	475	5.36	54	10	18
R insula	13		5.18	42	4	−2

BA = Brodmann area; L = left; R = right.

TABLE 3 Probabilistic labeling of posterior parietal cortex regions that showed greater activations during AWP solving compared with NWP solving

Assigned region	Probability of peak in assigned region (%)	% of region activated	% of cluster in region	Peak activation coordinates		
				x	y	z
L IPS (hIP3)		78.2	11.6			
L IPS (hIP1)		53.4	13			
L SPL (7A)	80	24.7	21.7	-14	-64	54
L SMG (PF)	80	21.5	11.2	-52	-36	48
R IPS (hIP3)	50	82.2	17.2	30	-56	44
R SMG (PFt)	30	50.5	15.1	56	-30	40
R SPL (7A)		16.9	12.5			
R SPL (7PC)		32.5	9			

arithmetic than nonarithmetic word problem solving. As shown in Figure 3 and Table 2, we detected widespread brain regions that showed greater activations during solving arithmetic word problems, compared with the nonarithmetic word problem condition along the bilateral fronto-insular-parietal circuits. The most extensive cluster centered on the left posterior parietal cortex (PPC) and covered the bilateral IPS and extended to the bilateral fusiform gyrus (FG) in the ventrotemporal occipital cortex (VTOC). Other significant clusters included the left and right middle frontal gyri (MFG) as well as right insula in the PFC, right hippocampus, and the left cerebellum.

We then examined whether brain responses toward arithmetic word problems varied depending on the mathematical problem size. To examine this, ROIs based on functional clusters where AWP activation was stronger than NWP were used to analyze beta-values for large versus small problems. The results showed no evidence of difference between large and small problems (all p s > 0.05, bonferroni corrected), possibly due to the limited number of trials per condition.

Next, to examine whether waiting 12 s to solve the problem introduced working memory load and contributing to frontoparietal activation, we modeled brain responses of the first 8-s epoch for each condition. The results are shown in Supporting Information Figure S2. The regions that showed greater activations for arithmetic over nonarithmetic word problems are highly consistent with modeling the entire 12-s problem duration (Figure 3). These results suggest that the fronto-insular-parietal activations identified in our results were not driven by prolonged problem presentation.

We then examined the spatial profile of the brain responses of PPC that showed greater activations during AWP than NWP using cluster labeling of cytoarchitectonic probabilistic maps. We focused on PPC regions by creating a mask that incorporated all parietal cortex subdivisions, including IPS, AG, supramarginal gyrus (SMG), and superior parietal lobule (SPL) and labeling the PPC cluster that was within the mask. The analysis showed that in the left PPC, the posterior IPS area hIP3 had the largest spatial extent of activations, followed by hIP1. In the right PPC, hIP3

TABLE 4 Brain regions that showed greater activations during NWP solving compared with AWP solving

				MNI coordinates		
Region	BA	# of voxels	Peak T-score	x	y	z
NWP > AWP						
L inferior frontal gyrus/	45	4,695	10.15	−58	20	4
L middle temporal gyrus/	40		9.79	−58	−28	−8
L orbital frontal gyrus/	47		8.25	−46	26	−18
L angular gyrus/	39		8.24	−60	−58	24
L temporal pole/	38		7.52	−46	14	−30
L inferior temporal gyrus	21		6.29	−60	−22	−20
L middle frontal gyrus	8	303	7.85	−36	24	42
L superior frontal gyrus/	8	2,066	7.77	−12	42	42
R superior frontal gyrus/	9		7.01	6	54	26
L supplementary motor area	6		4.30	−8	10	64
R middle temporal gyrus/	21	1,849	6.57	52	−24	−10
R orbital frontal gyrus/	47		5.97	48	30	−16
R middle temporal gyrus	19		5.36	60	−62	8
R cerebellum		496	6.33	24	−74	−38
L cerebellum		234	6.03	−24	−78	−38

BA = Brodmann area; L = left; R = right.

TABLE 5 Probabilistic labeling of posterior parietal cortex regions that showed greater activations during NWP solving compared with AWP solving

Assigned region	Probability of peak in assigned region (%)	% of region activated	% of cluster in region	Peak activation coordinates		
				x	y	z
L AG (PGa)	70	24.1	44.1	-46	-64	44
L AG (PGp)	30	8.5	21.8	-60	-60	22
L SMG (PFm)	30	11.6	13.9	-62	-52	14
L SMG (PF)		4.5	10.4			

(a) Right Intraparietal Sulcus **(b) Left Intraparietal Sulcus** **FIGURE 4** Relative signal strength between brain responses of arithmetic word problem (AWP) greater than nonarithmetic word problems (NWP) solving within the bilateral intraparietal sulcus (IPS) were predictive of response times of arithmetic word problem solution collected outside the scanner. Scatter plots are presented for illustration purpose. *** $p < 0.001$ [Color figure can be viewed at wileyonlinelibrary.com]

had the strongest and largest spatial extent of activations, followed by SMG and SPL subregions (Table 3).

3.3 | Nonarithmetic word problem solving resulted in more perisylvian cortex activations

We then examined brain regions that showed greater activation in nonarithmetic than arithmetic word problem solving. This analysis indicated considerable activation differences in widespread brain regions distinct from arithmetic over nonarithmetic word problems (see Figure 3 and Table 4). The most extensive cluster centered in the left inferior frontal gyrus (IFG) extending posteriorly to the left middle

temporal gyrus (MTG), inferior temporal gyrus (ITG), and angular gyrus (AG). Other significant clusters included the left MFG, left superior frontal gyrus (SFG) with adjoining supplementary motor area (SMA), right MTG with adjoining right AG, and the bilateral cerebellum.

Similar to the previous analysis, to ensure problem duration did not contribute to extra brain activations, we then examined the contrast by modeling brain responses of the first 8-s epoch of the solution period. The results are shown in Supporting Information Figure S2. Consistently, the regions that showed greater activations for nonarithmetic over arithmetic word problems are highly similar with modeling the entire 12-s problem duration (Figure 3), suggesting the results are not driven by prolonged problem presentation.

TABLE 6 Brain regions that showed correlations between the response time of arithmetic word problem solving and signal strength difference of AWP greater than NWP

Region	BA	# of voxels	Peak T-score	MNI coordinates		
				x	y	z
AWP > NWP						
R lateral occipital gyrus/angular gyrus	19/39	184	6.59	36	−78	32
L supramarginal gyrus	39	210	5.78	−56	−52	36
L intraparietal sulcus	39		5.40	−40	−52	40
R angular gyrus	39	183	4.76	54	−48	30
R intraparietal sulcus	40		4.46	46	−48	46

TABLE 7 Probabilistic labeling of posterior parietal cortex regions that showed correlations between response time of AWP and signal strength difference of AWP greater than NWP

Assigned region	Probability of peak in assigned region (%)	% of region activated	% of cluster in region	Peak activation coordinates		
				x	y	z
L IPS (hIP1)	50	23.3	57.5	-40	-52	40
L SMG (PFm)	70	9.3	26.1	-56	-52	36

We then conducted cluster labeling analysis of the brain responses of nonarithmetic over arithmetic word problem solving within PPC using the cytoarchitectonic probabilistic maps. This analysis only identified one cluster in the left PPC. Within this cluster, the anterior portion of AG-PGa had the greatest and largest spatial of activations, followed by the posterior PGp. PGa and PGp together accounted for 65.9% of the PPC cluster (Table 5).

3.4 | IPS activations are predictive of arithmetic word problem solving outside the scanner

Next, we investigated the relationship between individual differences in word problem solution and brain activations. Because the accuracy was close to ceiling and had little variability, we focused on examining the correlation between out-scanner RT and activation level difference between the two problem types at the whole brain level. As shown in Figure 4 and Table 6, positive correlations were observed between out-scanner RT of arithmetic word problem solving and the activation level difference between AWP over NWP in the left IPS with adjoining supramarginal gyrus (SMG), the right IPS and adjacent AG, as well as the right lateral occipital gyrus. No correlation was

found between the RT of nonarithmetic word problem performance and the contrast image of NWP over AWP.

In order to localize the individual differences and to further investigate the predictive ability of the PPC responses over behavioral performance, probabilistic cluster labeling was conducted on the left and the right PPC clusters. This analysis indicated that only left clusters were identified within the anatomically defined PPC mask, with the left hIP1 accounting for 57.5% of the cluster, suggesting that most of the activity fell within the left IPS (Table 7).

3.5 | Arithmetic word problem solving is associated with strengthened task-dependent fronto-parietal connectivity

Finally, to further investigate functional circuits associated with arithmetic word problem solving, we conducted a PPI analysis of task-dependent functional connectivity using rAI as the seed region. One-sample *t*-tests of rAI connectivity for the contrast of AWP-NWP were assessed across the entire brain. We found that compared with nonarithmetic versions, arithmetic word problems engaged greater rAI connectivity with multiple regions, most predominantly in the right and the left intraparietal sulcus in the PPC and dorsal anterior cingulate cortex (dACC). Other significant clusters included the left thalamus, middle occipital gyrus, and right precuneus (Figure 5, Table 8). Nonarithmetic word problem solving, in contrast, did not reveal any stronger rAI connectivity compared with arithmetic word problems.

4 | DISCUSSION

In the current study, we investigated neural mechanisms of word problem solving and how the neural systems modulated individual differences in behavioral competence for young adults that are proficient in arithmetic skills. We compared brain responses during word problem solving that required one-step arithmetic operations and during narrative sentence evaluation that only required context comprehension. This task design allowed us to compare arithmetic word problem solutions with reading of sentences that did not require calculation. Although the behavioral performance did not differ between the two problem types, BOLD signal varied substantially. More specifically, solving arithmetic word problems resulted in higher BOLD signal and more strengthened coupling in the fronto-insular-parietal circuits. In contrast, problems without quantity manipulation resulted in higher BOLD signal along the left sylvian fissure, including the MTG and extended posteriorly to the AG as well as IFG in the prefrontal cortex. Furthermore, only activities within the bilateral IPS activations were predictive of word problem solution fluency collected outside the

FIGURE 5 Brain regions that were functionally connected with right anterior insula (rAI) during arithmetic word problem solution. Psychophysiological interaction (PPI) analyses revealed greater rAI connectivity during arithmetic word problem solving, compared with the nonarithmetic word problems. Greater connectivity was observed in the dorsal anterior cingulate cortex (dACC) as well as the bilateral intraparietal sulcus (IPS) [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 8 Brain regions that showed greater rAI connectivity during AWP rather than NWP, revealed by PPI analyses

Region	BA	# of voxels	PeakT-score	MNI coordinates		
				x	y	z
AWP > NWP						
R supramarginal gyrus	40	787	6.03	48	−30	38
R intraparietal sulcus	7		4.69	36	−44	40
R postcentral gyrus	1/2/3		4.56	58	−16	36
L thalamus		157	5.49	−4	−16	18
L middle occipital gyrus	19	202	5.35	−52	−74	8
L paracingulate gyrus	32	441	5.33	−4	20	34
L intraparietal sulcus	40	320	4.95	−42	−44	40
R precuneus	31	224	4.95	24	−60	26

scanner. Our results are the first attempt using fMRI to demonstrate such brain response differences between reading problem sentences with and without manipulation of quantity information that are closely linked with behavioral saliency and cognitive strategy. Collectively these results have provided significant insights into how the brain solves arithmetic word problems, an omnipresent but challenging component of mathematical training.

The most important finding of our current study is that arithmetic and nonarithmetic versions of reading problem sentences elicit large amounts of BOLD signal and functional connectivity variability uniquely localized to each task type. Remarkably, the degree of matching in sentence content and performance parameters of the two sets of problems resulted in highly distinctive patterns that conform precisely to expectations on mathematical model building versus standard sentence comprehension. More specifically, our results have demonstrated that arithmetic word problems are associated with the fronto-insular-parietal circuits, including the bilateral IPS in the PPC, rAI, as well as MFG in the DLPFC. Neurocognitive models of arithmetic problem solving have highlighted a critical role of the fronto-insular-parietal circuits in numerical task performance (Ansari, 2008; Chang et al., 2015; 2016; Houde et al., 2010; Rosenberg-Lee, Chang, et al., 2011; Wu et al., 2009). Brain activations within the IPS are typically stronger toward mathematical knowledge rather than nonmathematical knowledge (Amalric & Dehaene, 2016; Newman et al., 2011; Thioux et al., 2005; Zhou et al., 2018), such as number comparison than animal category judgment (Thioux et al., 2005), in evaluating sentence with high-level mathematical knowledge such as algebra than general knowledge (Amalric & Dehaene, 2016), and in numerical problem solving rather than verbal problem solving (Newman et al., 2011). Meta-analyses over children, adolescents, and adults showed that the rAI node is consistently activated during number operation (Arsalidou & Taylor, 2011; Houde et al., 2010). Activations in the DLPFC, mainly the MFG, were associated with information retention and manipulation during working memory (Miller & Cohen, 2001; Rottschy et al., 2012), two abilities which are typically used when solving numerical problems (Chang et al., 2015; Menon et al., 2014), especially during effortful tasks that require more quantity manipulation (De Smedt, Holloway, & Ansari, 2011; Wu et al., 2009). Furthermore, coupling with the IPS within the PPC, DLPFC makes up the major component of central executive network (Menon, 2015), which serves as working memory, constructs problem solutions, and is

responsible for goal-oriented decision making in the executive control processes (Buchsbaum, Greer, Chang, & Berman, 2005; Rottschy et al., 2012). Together these findings confirm that the prefrontal area extending to insular cortex that formed the cognitive control circuits with posterior parietal cortex showed a critical role during solving word problems that require numerical calculation. This network sustained arithmetic word problem solutions not only by increasing local functional engagement, but also by strengthening within the network during the solution process.

Note that an overlap between arithmetic and nonarithmetic word problems against baseline is observed in the MFG and IPS (see Supporting Information Figure S3), indicating that the domain-general cognitive control process is involved in the solution of both problem types. Importantly, although participants responded more accurately toward AWP than NWP in the out-of-scanner task, this is likely due to speed-accuracy tradeoff, as the response times of NWP solutions were slightly slower than AWP (see Figure 2). To confirm the possibility, we calculated an efficiency measurement by combining both accuracy and RT scores, as this method has the advantage of considering both speed and accuracy into a single variable (Salthouse & Hedden, 2002). This measurement did not differ between the two problem types. Consistently, both the in-scanner accuracy and RT did not show difference between the two conditions. Collectively, these results support a model for arithmetic word problem solving where additional interregional coupling over the fronto-insular-parietal network is not driven by general task difficulty. When contrasted with the reduced load for text- and judgment-matched narrative problems, the need for the increased recruitment for arithmetic word problems is likely a result of the remaining component not matched by the narrative problems: extra loading of quantity-based manipulation in working memory of the mathematical problem model. This explanation is further supported by the result of the PPI analysis showing coupling between the salience network for only the arithmetic task, and only to the IPS.

Reading nonarithmetic word problems, in contrast, engaged to a greater level, brain regions associated with temporal cortices, most predominantly in the left IFG extending along the sylvian fissure to MTG and AG. These regions form the canonical language network (Shirer, Ryali, Rykhlevskaia, Menon, & Greicius, 2012). These findings are consistent with results of a study by Zhou et al. wherein word problems with more verbal reasoning activated stronger AG and MTG than word problems with large number quantity (Zhou et al., 2018)

and another study by Newman et al. where corresponding problems presented in verbal formats activated stronger IFG than those in equation format (Newman et al., 2011). Neuroimaging studies have found that IFG showed greater engagement during reading of pseudowords and real words with irregular spellings (e.g., *pint*) relative to highly familiar real words (Fiez & Petersen, 1998), suggesting that the left IFG was associated with effortful articulatory programming of phonological coding during reading (Fiez & Petersen, 1998; Pugh et al., 2000, 2001). The left MTG within the lateral temporal cortex was linked to semantic processing during reading context (Binder & Desai, 2011; Humphries, Binder, Medler, & Liebenthal, 2006; Kocagoncu et al., 2017). The MTG and AG are the anchor of long-term storage of semantic memory and play a critical role in integrating semantic information during processing verbal materials (Binder & Desai, 2011; Blumenfeld, Booth, & Burman, 2006; Fiebach et al., 2002; Rossell, Price, & Nobre, 2003). These regions were identified to show recruitment when perceiving semantically congruent sentences compared with sentences generated by random word sequences (Humphries et al., 2006) as well as perceiving familiar real words compared with pronounceable pseudowords without actual semantic information (Fiebach et al., 2002). In line with these previous efforts, transcranial magnetic stimulation administered to bilateral lateral temporal cortex has also been found to impair semantic decision, such as in a synonym judgment task (Lambon Ralph, Pobric, & Jefferies, 2009). Studies assessing intrinsic connectivity during resting state have also reported that intensified circuits between prefrontal cortex and MTG were predictive of better reading comprehension competence in both children and adults (Chang et al., 2018; Koyama et al., 2011). Together with these previous findings, our results have further supported that reading sentences without numerical operations mainly involves phonology decoding and semantic integration from the contextual information. In line with the literature, the current study further confirms that reading sentences with and without arithmetic processing engages distinct brain responses that are behaviorally salient to each task (Amalric & Dehaene, 2016; Thioux et al., 2005; Zhou et al., 2018).

Our results have demonstrated functional heterogeneity of the two problem types in the posterior parietal cortex. As hypothesized, arithmetic word problem solving is associated with IPS, whereas non-arithmetic word problem solving is associated with the left AG, supporting the heterogeneity of the PPC during word problem solution. The IPS has been a primary focus of research into arithmetic word problem solving from pediatric to adult samples (Arsalidou & Taylor, 2011; Chang et al., 2016, 2018; Houde et al., 2010). This system has long been considered as representing abstract quantity information and associated with procedural calculation (Arsalidou & Taylor, 2011; Cohen Kadosh et al., 2008; Dehaene et al., 2003) and plays an obligatory role in numerical problem solving (Wu et al., 2009). Converging evidence has consistently identified an obligatory role of the IPS in numerical tasks ranging from simple number comparison, single and multi-digit arithmetic calculation, and even more complicated algebra and calculus integrals (Cohen Kadosh et al., 2008; Dehaene, Molko, Cohen, & Wilson, 2004; Krueger et al., 2008; Wu et al., 2009), with IPS engagement also increasing with problem size and mathematical difficulty (Chang et al., 2015; De Smedt et al., 2011). This matches our

results such that the mathematical model embedded within the arithmetic word problems include both single- and double-digit calculation which increase the load of quantity manipulation, and hence engage greater IPS activation. Notably, our results suggested that the advantage of arithmetic word problems in the IPS is bilateral (Figure 3). The right IPS has been considered as format-independent abstract quantity representation whereas the left IPS has been associated with symbolic numerical processing (Holloway & Ansari, 2010). Our results, therefore, would seem to demonstrate the crucial involvement of both symbolic decoding from Arabic numerals and magnitude manipulation that is independent of the problem format which are necessary during solution of arithmetic word problems.

The AG is ventral to the IPS. The functional role of AG is even more segregated. In the semantic retrieval system proposed by Binder and colleagues, anterior AG subdivision, PGa, with the MTG, have been postulated as playing a significant role of semantic manipulation (Binder et al., 2009). The posterior subdivision, PGp, is inversely associated with task difficulty, showing significant deactivation (activation below the resting baseline) as task difficulty increases (Rosenberg-Lee, Chang, et al., 2011; Wu et al., 2009). Consistently, our results demonstrated that nonarithmetic word problems were exclusively associated with the anterior portion of AG, particularly in the left hemisphere. These results suggested that reading and comprehending sentences that do not require mathematical models requires a greater level of semantic-based processing anchored in the memory system. Certain processes are not involved in reading arithmetic sentences, possibly due to problem mathematical models that included both single- and double-digit operations and hence forced problem solvers to focus on the higher level of quantity manipulation and procedural calculation. Together, our results have further supported the behaviorally salient functional heterogeneity of the posterior parietal cortex during reading word problem sentences that involve distinct strategies.

A final important finding of our results is that PPC responses are predictive of arithmetic word problem performance collected outside the scanner at a different time point. More specifically, reduced PPC activation is associated with more efficient word problem solving, even in adults with mature problem solution skills. Cytoarchitectonically labeled analyses have further localized the brain-behavior association into the *hIP1* within the IPS. This is consistent with previous results that low achieving individuals showed higher IPS activation than higher achieving individuals (Price, Mazzocco, & Ansari, 2013). Our results therefore indicate that the inefficient word problem solvers rely on greater level of quantity manipulation and procedural calculations. These results might further suggest that when solving word problems, slow solvers focus on the problem mathematical model, whereas the efficient solvers pay relatively less attention on processing the numerical operation, perhaps rather on problem description. Further investigations are needed to clarify the core deficits of cognitive components during word problem solution.

For the past several decades, neuroimaging studies have provided abundant evidence to probe the effect of brain function for key cognitive skills. The approach has boosted efforts of investigating how individual differences in brain responses support behavioral performance. Here we provide evidence of neurobiological underpinnings for the brain representation of word problem solving, one of the most

omnipresent but challenging pedagogical practices which teach individuals to transfer mathematical knowledge into real-world utility. Contrary to the misconception that solving word problem is a specific form of text reading, our findings show, for the first time, that the localized neural engagement and functional circuits of reading arithmetic word problem sentences is remarkably distinct from reading parallel narrative sentences without a mathematical model that only required comprehending passage context. More critically, brain responses associated with quantity manipulation during arithmetic word problem solving uniquely predicts how efficient problem solvers are at deriving problem answers. Such neural characterization provides a scaffold for fractionating distinct cognitive components and strategies for arithmetic problem solving. Future studies investigating developmental progression of word problem solving skill acquisition would profit from understanding of brain mechanisms underlying learning, provide linkage between neuroscience and education, and promote better strategies for remediating deficits and enhancing instructional design in school curriculum.

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SUPPORTING INFORMATION

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