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The neural correlates of retrieval and procedural strategies in mental arithmetic: A functional neuroimaging meta-analysis

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Abstract
Mental arithmetic is a complex skill of great importance for later academic and life success. Many neuroimaging studies and several meta-analyses have aimed to identify the neural correlates of mental arithmetic. Previous meta-analyses of arithmetic grouped all problem types into a single meta-analytic map, despite evidence suggesting that different types of arithmetic problems are solved using different strategies. We used activation likelihood estimation (ALE) to conduct quantitative meta-analyses of mental arithmetic neuroimaging ($n = 31$) studies, and subsequently grouped contrasts from the 31 studies into problems that are typically solved using retrieval strategies (retrieval problems) ($n = 18$) and problems that are typically solved using procedural strategies (procedural problems) ($n = 19$). Foci were compiled to generate probabilistic maps of activation for mental arithmetic (i.e., all problem types), retrieval problems, and procedural problems. Conjunction and contrast analyses were conducted to examine overlapping and distinct activation for retrieval and procedural problems. The conjunction analysis revealed overlapping activation for retrieval and procedural problems in the bilateral inferior parietal lobules, regions typically associated with magnitude processing. Contrast analyses revealed specific activation in the left angular gyrus for retrieval problems and specific activation in the inferior frontal gyrus and cingulate gyrus for procedural problems. These findings indicate that the neural bases of arithmetic systematically differs according to problem type, providing new insights into the dynamic and task-dependent neural underpinnings of the calculating brain.

KEYWORDS
arithmetic, expertise, mathematical thinking, meta-analysis, neuroimaging, strategy

1 | INTRODUCTION

Arithmetic skills, which are the ability to perform arithmetic operations including addition, subtraction, multiplication, and division, are foundational skills upon which higher-order numerical competence is built. There is a fundamental link between the neural correlates that support arithmetic ability and later achievement (Grabner et al., 2007; Price et al., 2013). Given this, many functional neuroimaging studies have canvassed the brain intending to uncover the neural correlates that support arithmetic performance (e.g., Grabner, Ischebeck, et al., 2009; Rosenberg-Lee et al., 2015; van Eimeren et al., 2010; Venkatraman et al., 2005). Prior meta-analyses of this literature indicate that arithmetic processing is supported by a large frontoparietal network (Arsalidou & Taylor, 2011; Hawes et al., 2019). However, this conclusion is based on an undifferentiated view of arithmetic and fails to consider potential differences in brain regions that support arithmetic problems that are solved using different strategies. The present pre-registered meta-analysis aims to address this gap.

Arithmetic problems can be solved using a diversity of strategies. Common strategies used to solve arithmetic problems include fact retrieval (i.e., knowing the answers to problems without calculating) and procedural calculation (e.g., using fingers to add or decomposing problems into multiple steps) (Zamarian et al., 2009). Previous research has revealed that different arithmetic strategies are associated with the activation of different parts of the brain (e.g., Grabner, Ischebeck, et al., 2009). Self-report strategy use is a key method that has been used to uncover brain regions associated with strategy during arithmetic problem-solving. Specifically, following completion of an arithmetic task in a neuroimaging scanner, subjects are asked to indicate what strategies they used to solve problems and these strategy reports are then used to sort the neuroimaging data by self-reported strategy. In both children and adults, fact retrieval strategies have been associated with increased activation in the left angular gyrus, whereas procedural calculation strategies have been associated with widespread activation in the frontoparietal network (Grabner, Ansari, et al., 2009; Polspoel et al., 2017). Researchers have also aimed to identify brain regions that support retrieval compared to procedural strategies using methods that do not rely on subjective assessments of strategy use by comparing brain activation for different problem types. For instance, comparing brain activation during multiplication compared to subtraction, as these problem types are thought to be solved using different strategies (Imbo & Vandierendonck, 2008). Comparisons of brain activation during the solving of small and large arithmetic problems have also been used as a proxy for comparing brain regions supporting retrieval compared to procedural strategies. For example, in adults, complex arithmetic problems with large numbers (i.e., numbers > 10) are typically solved using calculation, whereas small problems (i.e., problems where both operands are <10 and particularly within addition and multiplication operations) are typically solved using direct memory retrieval (Dehaene & Cohen, 1997; Imbo & Vandierendonck, 2008; Thevenot et al., 2007; Zamarian et al., 2009). Similarly, an examination into the neural basis of the problem size effect, a robust phenomenon showing that participant's arithmetic performance declines as the magnitude of the operands in an arithmetic problem increases, consistently reveals that the left angular gyrus is more strongly activated for small compared to large problems (De Visscher et al., 2015; Delazer et al., 2005; Kong et al., 2005). The left angular gyrus also exhibits greater activation in response to arithmetic problems that the participant must verify as correct or incorrect when the solution is associated with a different operation (e.g., $9 \times 6 = 15$ is incorrect, but $9 + 6 = 15$ is correct), providing less subjective evidence that the left angular gyrus is associated with automatic arithmetic fact retrieval (Grabner et al., 2013). Relatedly, arithmetic training studies, in which participants become more fluent with arithmetic following training, reveal that arithmetic training leads to a shift from frontoparietal activation to greater activation in the left angular gyrus during arithmetic problem-solving (Delazer et al., 2003, 2005; Ischebeck et al., 2006; Zamarian et al., 2009). This frontoparietal shift has also been reported in children as they become more fluent with arithmetic (Rivera et al., 2005).

Although there is a large body of work that supports the idea that the angular gyrus is associated with arithmetic retrieval, other research contradicts this idea. Consequently, the specific functional role played by the left angular gyrus in arithmetic processing remains controversial. For instance, similarly to adults, children who were trained on arithmetic multiplication showed greater activity in the intraparietal sulcus and prefrontal cortex for untrained compared to trained problems following training. However, unlike adults, children do not exhibit greater activity in the angular gyrus for trained compared to untrained problems (Declercq et al., 2022). This suggests that the neural correlates supporting the learning of arithmetic facts in children differ compared to adults. Even in adults, some research comparing brain activation across arithmetic problem types (which differ with the degree to which individuals use calculation and retrieval strategies; Imbo & Vandierendonck, 2008), fail to demonstrate greater activation in the angular gyrus for operations associated with retrieval strategies (i.e., multiplication) compared to calculation strategies (i.e., subtract) (e.g., Chochon et al., 1999; Rosenberg-Lee et al., 2011). Moreover, functional differences that are observed in the angular gyrus may actually be driven by deactivation for arithmetic when compared to a number identification control task (Rosenberg-Lee et al., 2011). Similarly, with respect to training studies, while the angular gyrus consistently exhibits greater activation for trained compared to untrained problems measured during a post-training session, there is no signal change in the angular gyrus when activation for trained problems is compared to activation for the same problems measured during a pre-training session (Bloechle et al., 2016). Recent empirical studies that conflict with the idea that the angular gyrus plays a key role in verbal retrieval of math facts instead propose that arithmetic retrieval may be supported by a connected brain network long known to serve long-term memory functioning that includes the angular gyrus but also the hippocampus, parahippocampus, and retrosplenial cortex (Bloechle et al., 2016; Qin et al., 2014). If arithmetic retrieval is indeed supported by the long-term memory system, the activation of the left angular gyrus may reflect a domain-general role for attention allocation during memory retrieval in general, rather than a specialized region for verbal arithmetic fact retrieval (Cabeza et al., 2012). Taken together, a large body of research suggests that the left angular gyrus plays a key role in arithmetic fact retrieval. However, not all researchers have reached this conclusion and thus there is a need to analyze the existing body of data to distil the consistent patterns of activation during different types of arithmetic problem-solving. In view of this, the present meta-analysis looks to provide further insights into the role of the left angular gyrus during arithmetic processing.

As noted earlier, prior meta-analyses have concluded that arithmetic is supported by a frontoparietal network (Arsalidou & Taylor, 2011; Hawes et al., 2019). However, all previous syntheses of neuroimaging studies on arithmetic processing grouped diverse arithmetic problem types into one general category: arithmetic. Due to empirical findings suggesting that arithmetic problems solved using retrieval compared to procedural strategies are supported by different brain systems (e.g., Delazer et al., 2003; Grabner et al., 2013; Grabner, Ischebeck, et al., 2009; Zamarian et al., 2009) these previous meta-analyses may obscure striking differences in the way the brain processes different kinds of arithmetic problems. Uncovering the commonalities across empirical studies on the neural correlates of retrieval compared to procedural problem-solving is theoretically valuable as it illuminates how our brains implement distinct strategies to efficiently accomplish the complex and uniquely human demands of mental arithmetic. In addition, this fine-grained analysis of specific strategies explores how experience and expertise are instantiated at the neural level. This work also has practical significance as the use of a retrieval strategy is associated with enhanced arithmetic fluency (i.e., being able to solve problems faster and more accurately), which in turn is predictive of greater mathematical competence and reduced chance of having a math disability (e.g., Berteletti et al., 2014; De Smedt et al., 2011; Peters & De Smedt, 2018; Price et al., 2013). Thus, it is critical to separately examine arithmetic problems solved using retrieval compared to procedural strategies at the meta-analytic level. Taken together, this study aims to provide a comprehensive account of the neural bases of arithmetic according to problem type (retrieval vs. procedural), providing new insights into the dynamic and task-dependent neural underpinnings of the calculating brain.

2 | THE PRESENT META-ANALYSIS

In the present study, we use activation likelihood estimation (ALE) to conduct quantitative meta-analyses to identify convergent brain regions across multiple empirical studies to identify the neural correlates of mental arithmetic. Following this, we construct theoretically driven groups of contrasts comprised of arithmetic problem types that are typically solved using a retrieval strategy (retrieval problems) (e.g., 2 + 3) and arithmetic problem types that are typically solved using a procedural strategy (procedural problems) (e.g., 43–27, or 4 + 3–7), and examine the neural correlates retrieval and procedural problems, independently. In addition, we compute conjunction and contrast analyses between the retrieval and procedural arithmetic maps to identify quantitatively overlapping and distinct brain regions that support these arithmetic strategies. Based on previous empirical studies, we predict that the general mental arithmetic map (i.e., the map that includes all arithmetic problem types) will replicate previous meta-analytic findings to reveal that a frontoparietal network supports mental arithmetic across problem types. However, we also predict that our quantitative synthesis of retrieval and procedural arithmetic problems, individually, will reveal that arithmetic problems solved using retrieval and procedural strategies are supported by distinct systems. Specifically, we predict that procedural problems will associate with a frontoparietal network, typically activated during calculation, whereas retrieval problems will associate with activation in the left angular gyrus, a region typically related to fact retrieval. All research questions, methods (including literature search terms, inclusions/exclusion criteria) analyses, and predictions were preregistered and time stamped on the open science framework (https://osf.io/kty2m).

3 | METHOD

Methods and analyses of the present study were pre-registered on the OSF (https://osf.io/kty2m). The single-file ALE arithmetic map reported in Hawes et al. (2019) was used to identify all relevant mental arithmetic papers that were published before 2019. An additional literature review was conducted to find any additional papers that were not included in Hawes et al. (2019), or papers that were published following this meta-analysis. All reported methods and analyses follow this pre-registration.

This study used data from and contributed data to the Brainmap database (https://brainmap.org/). All tools used to conduct the meta-analyses are registered with Neuroimaging Informatics Tool and Resources Clearinghouse (NITRC) and the Neuroscience Information Framework (NIF).

3.1 | Literature review

Relevant research articles were identified using a stepwise procedure. First, we ran a standard search of the PUBMED and PsychInfo databases using combinations of the following terms: 'addition', 'subtraction', 'division', 'multiplication', 'arithmetic', 'mental math', 'simple arithmetic', and 'mental arithmetic'. Following this, we reviewed the reference sections for any relevant papers that may not have shown up in the initial search. A study was considered for inclusion if it contained an active or passive task that required the participant to perform an arithmetic calculation using symbolic numbers. This literature search produced three potential additional empirical papers (i.e., papers not included in Hawes et al. (2019)). However, none of the three papers contained contrasts that fit our inclusion criteria. Therefore, the final set of empirical papers included in the current meta-analysis were all included in the meta-analysis by Hawes et al. (2019).

3.2 | Inclusion/exclusion criteria

The following criteria were used to determine whether a study would be included in any of the three arithmetic maps:

1. Studies must have used at least one of the following tasks: addition, subtraction, multiplication, division.
2. Studies must have included a group of healthy adults.
3. Studies must have reported whole-brain group analyses with stereotactic coordinates in Talairach/Tournoux or Montreal Neurological Institute (MNI) space.

   a. Contrasts that used region of interest (ROI) or multivariate statistical approaches were excluded because including them leads to inflated significance for those regions (Müller et al., 2018).
4. Neuroimaging must have been done using fMRI or PET imaging methods.
5. Studies must have included contrasts with active control conditions.
   a. Studies that included only contrasts against baseline, rest, or fixation were excluded.
6. Studies must have been published in English.

Contrasts from the full mental arithmetic meta-analysis were then used to construct theoretically informed groups based on the arithmetic processing literature (e.g., Bloechle et al., 2016; De Smedt et al., 2011; Grabner, Ischebeck, et al., 2009; Imbo & Vandierendonck, 2008; Peters & De Smedt, 2018; Polspoel et al., 2017; Thevenot et al., 2007). The contrasts were grouped based on the degree to which adults were likely to solve the problem using retrieval and procedural strategies. The specific inclusion criteria for the retrieval and procedural maps are detailed below.

The *retrieval problems map* included the following contrast types:

- Arithmetic > control task
- Retrieval > procedural
- Easy problems > hard problems
- Arithmetic task > basic number processing task
- Reverse problem size effect
- Contrasting operation types, A > B

For a contrast to be included in the retrieval problems map, the experimental condition had to fit the following criteria, and simultaneously, the control condition could not fit the following criteria. For example, for an easy > hard problems contrast to be included, easy, but not hard problems, must fit the following criteria:

- The problem had two or fewer operands.
- Neither operand was a negative number.
- The participant reported using a retrieval strategy.
- For addition problems (augend + addend = sum), the augend and the addend were both 10 or lower.
- For subtraction problems (minuend – subtrahend = difference), the minuend and subtrahend were both single-digit numbers.
- For multiplication problems (multiplicand x multiplier = product), the multiplicand and the multipliers were both 11 or less.
- For division problems (dividend/divisor = quotient), both the dividend and the divisors were 11 or less or the resulting quotient was a whole number

The *procedural problems map* included the following contrast types:

- Arithmetic > control task
- Procedural > retrieval
- Hard problems > easy problems
- Arithmetic task > basic number processing task
- Problem size effect
- Contrasting operation types, A > B

For a contrast to be included in the procedural problems map, the experimental condition had to fit the following criteria, and simultaneously, the control condition could not fit the following criteria. For example, for a hard > easy problems contrast to be included, hard, but not easy problems, must fit the following criteria:

- Contrasts that had more than two operands (e.g., 4 + 5–6) were included.
- At least one operand was a negative number.
- The participant reported using a procedural strategy.
- For addition problems (augend + addend = sum), at least one of the augend or addend was 11 or higher.
- For subtraction problems (minuend – subtrahend = difference), at least one of the minuend or subtrahend was a double-digit number.
- For multiplication problems (multiplicand x multiplier = product), at least one of the multiplicand or the multipliers were 12 or greater.
- For division problems (dividend/divisor = quotient) at least one of the dividend or divisors were 12 or greater or the resulting quotient was not a whole number.

Thirty-one studies were identified as relevant based on the literature search and inclusion/exclusion criteria and included in the meta-analyses. All included studies contained a mental arithmetic task. Together, these studies had a cumulative sample size of 533 healthy adult human participants and report 713 activation foci. Descriptive information for the included studies is reported in Table 1. All meta-analytic analyses were conducted in Talairach space. The Lancaster transformation (icbm2tal) was used to transform studies from MNI into Talairach space when the stereotaxic coordinates were reported in MNI space (Laird et al., 2010; Lancaster et al., 2007).

The variability in different criterion values between problem types is based on the a priori classification based on our understanding that subtraction problems are more often solved using a procedural strategy compared to other arithmetic problem types which are more often solved using a retrieval strategy (e.g., Campbell & Xue, 2001; Dehaene et al., 2003; Kong et al., 2005; Pollack & Ashby, 2018). Critically, while we developed a method to categorize contrasts based on our review of the literature, we recognize that other teams might prefer to include contrasts based on different criteria. In addition, there are individual differences in the degree to which individuals use retrieval and procedural strategies for particular problem types. Therefore, the text files used to create each meta-analytic map, derived using Sleuth, are available on the open science framework (https://osf.io/vqnt6/) and can be easily modified according to distinct theoretical grouping criteria.

TABLE 1 Studies included in the mental arithmetic meta-analyses

Author	Journal	*N*	Imaging method	Mean age	Gender	Tasks	Contrast name	Loc	Map inclusion
Andres et al. (2011)	*NeuroImage*	10	fMRI	21	10 M	Subtraction and multiplication of Arabic digits	Multiply and subtract	8	
							Multiply > subtract	7	Retrieval
Andres et al. (2012)	*NeuroImage*	18	fMRI	21.3	18 M	Subtraction and multiplication of Arabic digits	Arithmetic > letter reading	5	
							Multiplication > subtraction	2	Retrieval
Chochon et al. (1999)	*Journal of Cognitive Neuroscience*	8	fMRI	20–30	4 M 4F	Subtraction and multiplication of Arabic digits	Multiplication > control	12	Retrieval
							Subtraction > control	14	Procedural
							Multiplication > digit naming	4	Retrieval
							Multiplication > comparison	1	Retrieval
							Subtraction > digit naming	11	Procedural
							Subtraction > comparison	13	Procedural
							Subtraction> multiplication	4	Procedural
De Visscher et al. (2015)	*NeuroImage*	20	fMRI	29	10 M 10F	Multiplication of Arabic digits	Retrieval > non-retrieval	7	Retrieval
							Non-retrieval > retrieval	7	Procedural
Delazer et al. (2003)	*Cognitive Brain Research*	13	fMRI	30.5	7 M 6F	Complex multiplication (2 digit times 1 digit) and fact retrieval multiplication (1 digit times 1 digit)	Retrieval > number matching	14	Retrieval
							Untrained complex multiplication > number matching	13	Procedural
Fehr et al. (2007)	*Brain Research*	11	fMRI	26.8	5 M 6F	1 and 2-digit addition, subtraction and multiplication	Addition complex > addition simple (A)	17	Procedural
							Subtraction complex > subtraction simple (B)	18	Procedural
							Multiplication complex > multiplication simple (C)	9	Procedural
							Division complex > division simple (D)	15	Procedural
							Conjunction (A + B + C + D)	8	Procedural
Fehr et al. (2010)	*Neuropsychologia*	11	fMRI	26.8	5 M 6F	1 and 2-digit addition, subtraction and multiplication	Control group: complex > simple (B)	18	Procedural
Grabner et al. (2007)	*NeuroImage*	25	fMRI	25.65	25 M	1 and 2 digit multiplication	Multi-digit > single-digit	15	Procedural
							Single-digit > multi-digit	1	Retrieval
Grabner, Ansari, et al. (2009)	*Human Brain Mapping*	28	fMRI	26.86	28 M	Multiplication of Arabic digits	Multiplication > figural-spatial, Untrained	2	Procedural
Grabner, Ischebeck, et al. (2009)	*Neuropsychologia*	28	fMRI	26.86	28 M	Addition, subtraction, multiplication and division of Arabic digits	Retrieval > procedural	1	Retrieval
							Procedural > retrieval	9	

(Continues)

TABLE 1 (Continued)

Author	Journal	*N*	Imaging method	Mean age	Gender	Tasks	Contrast name	Loc	Map inclusion
Gruber et al. (2001)	*Cerebral Cortex*	6	fMRI	25.8	6 M	Multiplication of Arabic digits	Compound number calculation > result matching	7	Procedural
							Simple number calculation > result matching	8	Procedural
Gullick and Wolford (2014)	*Human Brain Mapping*	24	fMRI	19	12 M 12F	Addition and subtraction of positive and negative integers	Positive operand problems > negative-operand problems	7	Retrieval
							Negative operand problems > positive operand problems	8	Procedural
							Addition problems > subtraction problems	1	
							Subtraction problems > addition problems	11	
Hayashi et al. (2000)	*Journal of the Neurological Sciences*	10	PET	26.2	10 M	Serial number subtraction and multiplication	Subtra-task > count-task	5	Procedural
							Multi-task > count-task	4	Retrieval
Hugdahl et al. (2004)	*American Journal of Psychiatry*	12	fMRI	31	5 M 7F	Addition of Arabic digits	Mental arithmetic—vigilance, healthy subjects	4	Procedural
Ischebeck et al. (2006)	*NeuroImage*	12	fMRI	26.8	4 M 8F	Subtraction and multiplication of Arabic digits	Multiplication untrained > number matching	13	Procedural
							Subtraction untrained > number matching	21	Procedural
Jost et al. (2009)	*NeuroImage*	16	fMRI	24.5	6 M 10F	Single digit multiplication	Small multiplication > storage	16	Retrieval
							Large multiplication > small multiplication	8	
							Small multiplication > large multiplication	1	Retrieval
							Small multiplication > zero multiplication	1	Retrieval
							Small multiplication > storage, large multiplication > storage, zero multiplication > storage	12	
Keller and Menon (2009)	*NeuroImage*	49	fMRI	23.99	24 M 25F	Addition and subtraction in 3 operand equations	Conjunction (males and females) (calculationidentification)	9	Procedural
Knops and Willmes (2014)	*NeuroImage*	17	fMRI	24.9	8 M 9F	Addition and subtraction of Arabic digits	Subtraction > addition	10	
Kong et al. (2005)	*Cognitive Brain Research*	16	fMRI	28	7 M 9F	Addition and subtraction of double digits	Main effect of arithmetic type (subtraction > addition)	5	
							Main effect of procedure complexity (with carrying > without carrying)	4	Procedural
Kuo et al. (2008)	*Brain Research*	11	fMRI	21–29	6 M 6F	Single or dual addition and subtraction	Single addition > baseline	13	Procedural
							Single subtraction > baseline	17	Procedural
							Dual addition > baseline	15	Procedural
							Dual subtraction > baseline	21	Procedural
							Dual operation > baseline	26	Procedural

TABLE 1 (Continued)

Author	Journal	*N*	Imaging method	Mean age	Gender	Tasks	Contrast name	Loc	Map inclusion
Lee (2000)	*Annals of Neurology*	11	fMRI	25–35	6 M 5F	Subtraction and multiplication of Arabic digits	Multiplication > subtraction	6	
							Subtraction > multiplication	8	
Menon et al. (2000)	*Neuroimaging*	16	fMRI	20.28	8 M 8F	2 and 3 operand equations	3 s 3-operand equations > control equations	16	Procedural
							3 s 2-operand > control equations	6	Retrieval
							6 s 3-operand equations > control equations	5	Procedural
							6 s 2-operand equations > control equations	0	Retrieval
							Main effect, operands	3	
Pesenti et al. (2000)	*Journal of Cognitive Neuroscience*	8	PET	21–29	8 M	Single digit addition	Addition > comparison	2	Retrieval
							Addition > orientation, characters (masked with addition > rest)	5	Retrieval
Rosenberg-Lee et al. (2011)	*Neuropsychologia*	20	fMRI	23.9	11 M 9F	Addition, subtraction, multiplication and division of Arabic digits	Subtraction: calculation > Identification	5	Retrieval
							Multiplication: Calculation > Identification	6	Retrieval
							Division: Calculation > Identification	6	Retrieval
Soylu and Newman (2016)	*Cognitive Processing*	13	fMRI	24.67	7 M 6F	1 and 2-digit addition	Main effect of addition difficulty (two digit > single digit)	4	
							Main effect of addition difficulty (One digit > Two digit)	6	
Stanescu-Cosson et al. (2000)	*Brain*	7	fMRI	22–26	3 M 4F	Single digit addition and approximation	All calculation > letter Matching	16	Retrieval
							Small numbers > letter Matching	7	Retrieval
Tschentscher and Hauk (2014)	*NeuroImage*	26	fMRI		13 M 13F	1 and 2-digit addition and multiplication	Arithmetic fact retrieval > procedural strategies	6	Retrieval
							Procedural strategies > arithmetic fact retrieval	7	Procedural
Van Der Ven et al. (2016)	*Brain Research*	23	fMRI	21.04	8 M 15F	Addition and subtraction of Arabic digits	[(Arabic addition > arabic memory) > (dot addition > dot memory)]	24	Retrieval
Venkatraman et al. (2005)	*Neuropsychologia*	10	fMRI	20–25	7 M 3F	Single digit addition and approximation	Symbolic exact addition > control	5	Retrieval
							Symbolic approximate addition > control	7	Retrieval
							Conjunction (symbolic and nonsymbolic addition, exact and approximate)	5	Retrieval

(Continues)

TABLE 1 (Continued)

Author	Journal	N	Imaging method	Mean age	Gender	Tasks	Contrast name	Loc	Map inclusion
Zago et al. (2001)	*NeuroImage*	6	PET	21	6 M	1 and 2-digit multiplication	Retrieve > read	7	Retrieval
							Compute > read	14	Procedural
							Compute and retrieve > read conjunction	14	
							Compute > retrieve masked by compute > read	15	Procedural
							Retrieve > compute masked by retrieve > read	2	Retrieval
Zarnhofer et al. (2012)	*Behavioral and Brain Functions*	42	fMRI	23	20 M 21F	Subtraction and multiplication of Arabic digits	Subtraction > multiplication	13	Procedural
							Multiplication > subtraction	8	Retrieval

Foci, number of foci reported in contrast; fMRI, functional magnetic resonance imaging; PET, positron emission tomography; N, sample size of each study; M – Male, F – Female; Loc, location.
Note: All contrasts included in the table are included in the general mental arithmetic ALE map. The *Map Inclusion* column specifics which contrasts are included in the retrieval and procedural ALE maps.

3.3 | Analysis procedure

All meta-analyses were conducted using GingerALE (version 2.3.6), a freely available software developed by the Brainmap team (Eickhoff et al., 2009, 2012, 2017; Turkeltaub et al., 2012). ALE assesses the convergence of multiple foci from many different contrasts across a set of independent studies producing a single quantitative, coordinate-based meta-analysis (Eickhoff et al., 2009, 2012; Turkeltaub et al., 2012). Implementing this technique results in the ALE algorithm modelling the stereotaxic coordinates of the foci as Gaussian probability distributions. These probability distributions are centred around the peak coordinates, resulting in a probabilistic map of activation referred to as a modelled activation (MA) map. These three-dimensional (3D) maps of modelled activations (i.e., single data-set maps) are then used to compute conjunction and contrast (i.e., subtraction) analyses (Eickhoff et al., 2011).

3.4 | Single dataset analyses

GingerALE (version 2.3.6) was used to compute the single-file ALE meta-analyses for (1) mental arithmetic (a map that included all problem types), (2) retrieval problems and (3) procedural problems. All of the 31 included empirical studies identified by the literature search were included to create the mental arithmetic map (533 subjects, 80 contrasts, 713 foci), 18 were included in the retrieval problems map (307 subjects, 31 contrasts, 171 foci), and 19 were included in the procedural problems map (322 subjects, 34 contrasts, 417 foci). Thus, these samples meet the criterion for adequate power, which is 17–20 experiments for each single dataset meta-analysis (Eickhoff et al., 2017). All single-file ALE analyses were thresholded using a cluster-level correction of 0.05 with a cluster-forming (uncorrected) threshold of $p < .001$, generated from 1000 threshold permutations as this is the optimal thresholding technique available (Eickhoff et al., 2012).

3.5 | Conjunction and contrast analyses

GingerALE (version 2.3.6) was also used to compute conjunction and contrast analyses to identify areas of overlap and specificity for problems typically solved using a retrieval compared to a procedural strategy. Conjunction and contrast analyses were performed using an uncorrected threshold of $p < .001$ with 5000 threshold permutations and a minimum volume of 50 mm^3. The only correction available for conjunction and contrast analyses is false discovery rate (FDR) thresholding, which is not recommended to be used with Gaussian data (Chumbley & Friston, 2009). An uncorrected threshold is considered acceptable for conjunction and contrast analyses as these analyses only include clusters that have already passed the strict threshold of cluster-level .05 and uncorrected .001, used to create the single-file maps. Therefore, an uncorrected threshold of .001 in combination with an extent threshold, which suppresses clusters smaller than

50 mm,[3] was used, as it is stringent without masking any important regions (For review see Eickhoff et al., 2012).

4 | RESULTS

4.1 | Single dataset meta-analyses

Single dataset ALE meta-analyses were computed to examine converging foci for mental arithmetic (across all task types), retrieval problems, and procedural problems.

Mental Arithmetic: The mental arithmetic single-file map, which included all contrasts reported in Table 1, revealed convergent regions of brain activation in regions that spanned the frontal and parietal cortex as well as the insula (Figure 1, Table 2). This single-file map is an exact replication of the arithmetic map in Hawes et al. (2019).

Retrieval Problems: The retrieval problems single-file map, which included all contrasts reported in Table 1 listed as 'retrieval' under the column 'Map Inclusion', revealed convergent regions of brain activation in the bilateral parietal lobes and the left superior temporal gyrus (Figure 1, Table 2).

Procedural Problems: The procedural problems single-file map, which included all contrasts reported in Table 1 listed as 'procedural' under the column 'Map Inclusion', revealed convergent regions of brain activation in regions spanning the frontal and parietal lobes, cuneus and insula (Figure 1, Table 2).

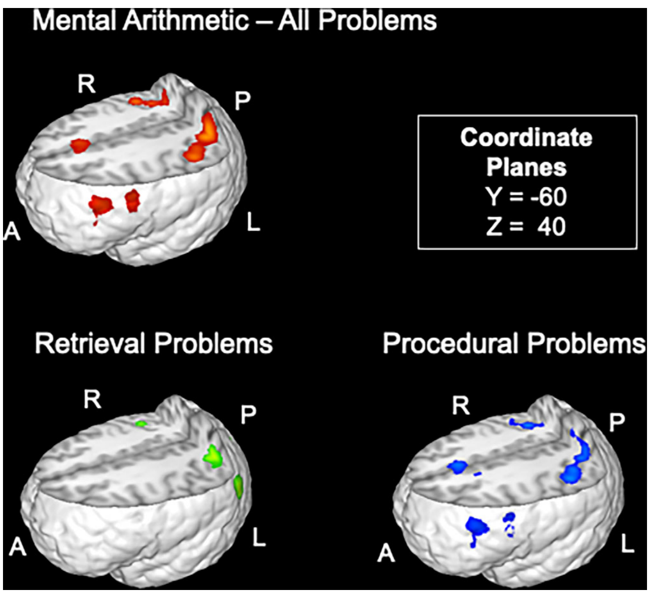

FIGURE 1 Single dataset ALE maps of mental arithmetic (both retrieval and procedural problems maps), retrieval problems, and procedural problems. These maps were generated using a cluster-level correction of 0.05 with 1000 threshold permutations and a cluster-forming (uncorrected) threshold of $p < .001$. Brain surface maps sliced at $Z = 40$ and $Y = -60$ are shown in Talairach space. Significant clusters of convergent brain clusters are reported in Table 2

4.2 | Conjunction ALE map (retrieval and procedural problems)

A conjunction analysis was computed to identify which brain regions were activated by both the retrieval and procedural problems single dataset ALE maps. Significant clusters of brain activation for retrieval and procedural problems converged in the left parietal lobe, spanning the inferior and superior parietal lobule, and the right inferior parietal (Figure 2, Table 3). All brain regions reported in this conjunction analyses were significant at $p < .001$ with a minimum cluster size of 50.

4.3 | Contrast ALE maps (retrieval and procedural problems)

Contrast analyses that compared the retrieval and procedural mental arithmetic single dataset ALE maps were conducted to reveal which brain regions were specifically activated during problem-solving of retrieval and procedural problems, respectively. Contrasting retrieval > procedural problems resulted in activation in the left middle temporal gyrus, superior temporal gyrus and angular gyrus while contrasting procedural > retrieval problems resulted in specific activation in the right cingulate gyrus and left inferior frontal gyrus (Figure 2, Table 3). All brain regions that were significantly associated with these contrast analyses were significant at $p < .001$ with a minimum cluster size of 50.

5 | DISCUSSION

The present study used ALE to examine patterns of brain activity related to mental arithmetic and to identify, compare, and contrast problems that are typically solved using retrieval and procedural strategies at the meta-analytic level. Findings from the mental arithmetic meta-analysis (i.e., the meta-analysis that included all arithmetic contrasts) converged with previous meta-analytic findings of arithmetic processing (e.g., Arsalidou & Taylor, 2011; Hawes et al., 2019; Pollack & Ashby, 2018) to show that arithmetic processing, across problem types, is supported by a large frontoparietal network. The present study went beyond identifying the brain system that supports all of mental arithmetic and examined theoretically-informed subtypes of arithmetic processing (i.e., retrieval vs. procedural arithmetic problems).

Given the large body of research suggesting that different brain regions associate with different underlying strategies during arithmetic problem-solving (Grabner, Ansari, et al., 2009; Thevenot et al., 2007), we predicted that retrieval and procedural problem maps would dissociate at the meta-analytic level. Indeed, procedural problems associated with a frontoparietal network that closely resembled the mental arithmetic map that included all contrasts (both retrieval and procedural problems). Conversely, the retrieval problems associated with convergent activation in a smaller set of regions in the parietal lobe, particularly, the left inferior parietal lobule (IPL). A

TABLE 2 Single dataset analyses (mental arithmetic, retrieval problems, procedural problems)

Hemisphere	Brain area	BA	X	Y	Z	ALE	Vol/mm
Mental arithmetic							
L	Inferior parietal lobule	7	−30	−56	42	0.0513	10,848
L	Superior parietal lobule	7	−28	−62	44	0.0480	
L	Inferior parietal lobule	40	−44	−38	40	0.0387	
L	Inferior parietal lobule	40	−40	−44	42	0.0313	
R	Precuneus	19	30	−66	40	0.0458	9144
R	Inferior parietal lobule	40	42	−42	44	0.0408	
R	Inferior parietal lobule	40	34	−50	42	0.0361	
L	Inferior frontal gyrus	9	−44	6	28	0.0691	6432
L	Middle frontal gyrus	9	−46	26	30	0.0275	
L	Superior frontal gyrus	6	−2	14	50	0.0332	5624
L	Superior frontal gyrus	8	0	18	48	0.0325	
L	Insula	47	−32	24	2	0.0364	2208
R	Insula	47	32	24	0	0.0382	2152
R	Middle frontal gyrus	9	48	14	26	0.0317	2000
L	Middle frontal gyrus	6	−26	−6	52	0.0246	1744
L	Middle frontal gyrus	6	−26	6	60	0.0228	
Retrieval problems map							
L	Precuneus	19	−30	−64	40	0.0245	3616
L	Precuneus	7	−26	−72	50	0.0145	
L	Inferior parietal lobule	40	−38	−56	42	0.0130	
L	Superior temporal gyrus	39	−56	−64	26	0.0205	952
R	Inferior parietal lobule	40	42	−40	40	0.0165	952
Procedural problems map							
L	Inferior parietal lobule	40	−44	−36	40	0.0274	6696
L	Superior parietal lobule	7	−28	−56	42	0.0271	
L	Inferior parietal lobule	40	−36	−44	38	0.0265	
L	Superior parietal lobule	7	−28	−62	44	0.0237	
L	Precuneus	7	−12	−62	50	0.0215	
L	Precuneus	7	−22	−70	42	0.0208	
L	Inferior frontal gyrus	9	−44	6	28	0.0414	5192
L	Middle frontal gyrus	9	−46	28	32	0.0203	
L	Middle frontal gyrus	46	−46	30	22	0.0144	
R	Inferior parietal lobule	40	34	−50	42	0.0271	3896
R	Precuneus	19	30	−66	38	0.0210	
R	Superior parietal lobule	7	28	−70	46	0.0201	
R	Precuneus	19	28	−58	36	0.0188	
R	Inferior parietal lobule	40	42	−40	40	0.0152	
R	Cingulate gyrus	32	4	18	42	0.0261	3680
L	Medial frontal gyrus	32	−10	10	44	0.0195	
R	Inferior frontal gyrus	9	48	14	24	0.0265	1952
R	Insula	47	32	24	0	0.0311	1824
L	Insula	13	−30	24	2	0.0279	1768
R	Cuneus	17	22	−92	−2	0.0284	1112
L	Middle frontal gyrus	6	−26	−8	52	0.0186	1064
L	Middle frontal gyrus	6	−34	−2	44	0.0130	
R	Middle frontal gyrus	10	40	40	18	0.0187	848
R	Middle frontal gyrus	46	44	32	20	0.0149	

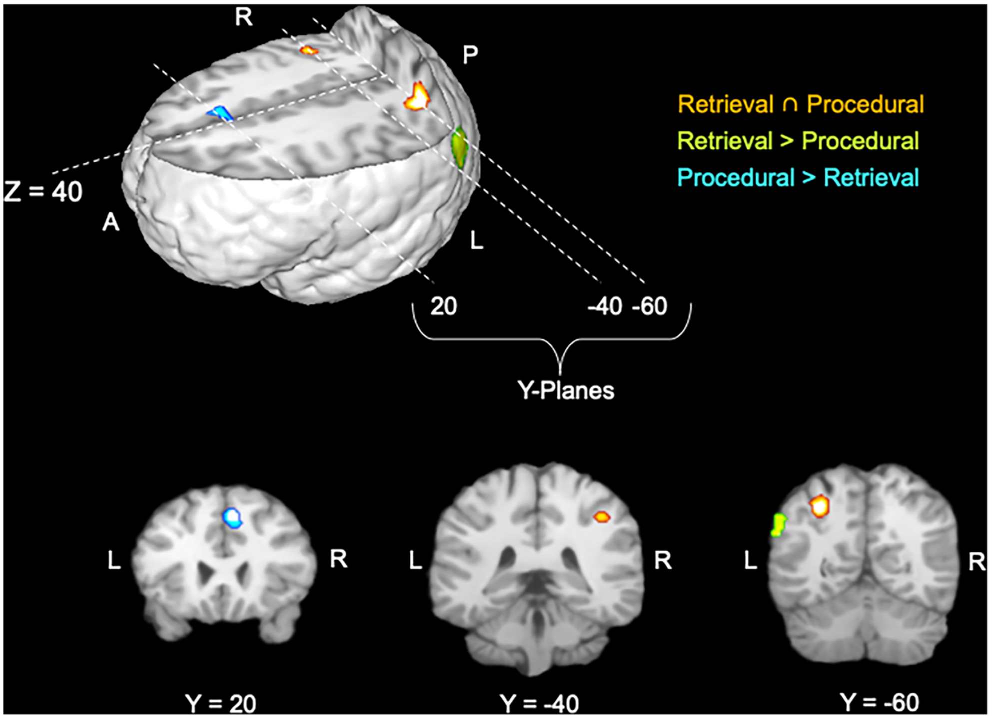

FIGURE 2 ALE maps from the conjunction and contrast analyses. The ALE conjunction analysis revealed significant clusters of convergence between retrieval and procedural problems (orange). ALE contrast analyses reveal specific activation for retrieval > procedural problems (green) and procedural > retrieval problems (blue). All conjunction and contrast analyses were conducted using an uncorrected $p < .001$ with 5000 permutations and a minimum volume of 50 mm3. Brain surface map is sliced at Z = 40 and Y = − 60, and brain slices are shown along the Y-plane at Y = 20, Y = −40, Y = −6. All maps are shown in Talairach space. Significant clusters from the conjunction and cluster analyses are reported in Table 3

TABLE 3 Conjunction and contrast analyses (retrieval problems, procedural problems)

Hemisphere	Brain area	BA	X	Y	Z	ALE	Vol/mm
Retrieval and procedural problems							
L	Superior parietal lobule	7	−28	−62	42	0.022	1648
R	Inferior parietal lobule	40	42	−40	40	0.015	280
L	Inferior parietal lobule	40	−40	−48	44	0.012	176
Retrieval > procedural							
L	Superior temporal gyrus	39	−55	−59	26	3.71902	800
L	Middle temporal gyrus	39	−51	−64	32	3.3528	
L	Angular gyrus	39	−54	−61	36	3.23888	
Procedural > retrieval							
R	Cingulate gyrus	32	7	19	45	3.71902	792
L	Inferior frontal gyrus	9	−45	16	22	3.71902	112

qualitative comparison of the individual meta-analytic maps in the current study (i.e., a visual examination of the similarities and differences between the single-file meta-analytic maps) suggests key differences in the neural regions that support the solving of arithmetic problems using retrieval versus procedural strategies.

Follow-up quantitative analyses were conducted to formally test this observation. Conjunction and contrast analyses were used to quantitatively compute overlapping and distinct brain regions associated with retrieval compared to procedural arithmetic problem solving (Eickhoff et al., 2011). The conjunction analysis revealed that the bilateral inferior parietal lobule was associated with both retrieval and procedural problems. The contrast analyses revealed that retrieval, compared to procedural, was associated with activation in the left angular gyrus spanning the temporal gyrus. Procedural, compared to retrieval, is specifically associated with activation in the frontal lobes, namely the right cingulate gyrus and left inferior frontal gyrus. Broadly, these findings highlight that mental arithmetic is a heterogeneous construct and that distinct brain systems support computations of different types of arithmetic problems.

5.1 | Clusters common to retrieval and procedural problems

Common to both the retrieval and procedural maps was activation of the bilateral IPL, with a larger cluster on the left that includes the superior parietal lobule (SPL). As the bilateral parietal lobes are associated with decision-making and response selection, it is possible that this overlapping region reflects similarities in task demands, even when only including contrasts with active controls (Göbel et al., 2004). However, the bilateral parietal lobules are also consistently implicated in basic number and magnitude processing, both within individual empirical studies and at the meta-analytic level (e.g., Arsalidou & Taylor, 2011; Cohen Kadosh & Walsh, 2009; Dehaene, 2007; Fias et al., 2003; Holloway et al., 2010; Kersey & Cantlon, 2017; Piazza & Izard, 2009; Sokolowski et al., 2017). Moreover, activation of the bilateral parietal lobules is associated with the processing of magnitude even in the absence of task demands, suggesting that these regions may be associated with representing magnitude, rather than decision-making or motor processing (Sokolowski et al., 2021). A recent study exploring the common neural correlates of basic number processing, measured using a symbol-quantity matching task and an arithmetic task, reports that basic number processing and arithmetic elicit overlapping activation in the bilateral parietal lobules and particularly the intraparietal sulcus (Matejko & Ansari, 2019). A complimentary meta-analysis that examined the conjunction of a mental arithmetic map (i.e., the same meta-analytic map used in the current study that includes both retrieval and procedural problems) and a basic number processing meta-analytic map revealed that arithmetic and basic number processing were both associated with activation in the right IPL and left IPL spanning into the SPL (Hawes et al., 2019). Together, this provides compelling evidence that the overlapping activation for retrieval and procedural problems instantiated in the bilateral parietal lobules might reflect the processing of magnitude. However, it cannot be discounted that this overlapping region may also reflect decision-making and motor responses common to retrieval and procedural problems.

5.2 | Clusters specific to retrieval and procedural problems

A single cluster in the left hemisphere spanning the angular gyrus, superior temporal gyrus, and middle temporal gyrus was the only region activated by retrieval, over and above procedural problems. The angular gyrus is a region that is associated with multiple functions across multiple cognitive domains including number processing, but also semantic processing, language, word reading and comprehension, and memory retrieval (for review see: Seghier, 2013). Within these domains, the angular gyrus acts as a 'cross-modal hub' that combines and integrates multisensory information to understand events, solve problems (particularly familiar problems), orient attention, and make sense of complex events. Within number processing, the strong activation in the angular gyrus has long been associated with arithmetic (Roland & Friberg, 1985); a finding that has been consistently replicated across several decades, particularly with problems of addition and multiplication (for reviews see, Vogel & De Smedt, 2021; Zamarian et al., 2009). Moreover, it has been suggested that this region supports the retrieval of arithmetic facts that are stored in verbal memory (Dehaene et al., 2003; Grabner et al., 2021; Seghier, 2013; Vogel & De Smedt, 2021). This idea aligns with findings suggesting that the angular gyrus plays a role in language and reading, further supported by a recent meta-analysis that revealed that arithmetic and phonological processing exhibit concordant activation in the left IPL, including the angular gyrus (Pollack & Ashby, 2018). However, other research into the role of the angular gyrus in arithmetic fact retrieval suggests that the angular gyrus might play an attentional role during arithmetic fact retrieval (Bloechle et al., 2016). This account is compatible with the idea that the angular gyrus is a cross-modal hub that dynamically connects with regions within brain networks. Yet, findings from the current meta-analysis do not provide evidence in support of other regions within the long-term memory system (e.g., the hippocampus, parahippocampus and retrosplenial cortex) being involved in arithmetic fact retrieval among adults. An explanation for these discrepant interpretations of the role of the angular gyrus in arithmetic is that the function of the angular gyrus is lateralized with the left angular gyrus being important for verbal fact retrieval (Grabner et al., 2013) and the right angular gyrus supporting visual–spatial fact retrieval during arithmetic (Arsalidou & Taylor, 2011). While further research is needed to enhance our understanding of the specificity of the role of the angular gyrus in arithmetic processing, cumulative evidence suggests that the left angular gyrus is involved in verbal fact retrieval. Therefore, we conclude that at the meta-analytic level, problems solved using retrieval strategies are supported by distinct brain regions from those solved using procedural strategies, with the left angular gyrus playing a particularly important role.

Procedural, compared to retrieval problems, were associated with activation in the frontal cortex and specifically the cingulate gyrus and left inferior frontal gyrus (IFG). The frontal cortex has long been linked to high-level cognitive functions including executive functioning, working memory, and mental manipulation (Gabrieli et al., 1998; Owen et al., 2005). The cingulate gyrus is specifically associated with attention and monitoring of performance and behaviour, but also the link between cognition and emotion (Carter et al., 1998). The IFG has also been linked to a wide range of behaviours including executive functioning measures, motor functioning, language production and empathy (Liakakis et al., 2011; Price, 2000). Within arithmetic, activation in the frontal lobes is more activated when participants are computing problems for which they have no training/practice (Delazer et al., 2003; Ischebeck et al., 2006). Moreover, frontal activation is associated with the self-report use of a procedural calculation strategy (Grabner, Ansari, et al., 2009). Given this, we conclude that the regions specific to the procedural problems map reflect the use of procedural calculation strategies that involve attention, working memory, and mental manipulation.

5.3 | Network approach to cognition

The current meta-analyses highlight common and distinct brain regions that support retrieval and procedural arithmetic problem-solving. Findings reveal key brain regions that are specific to different arithmetic problem types. Critically, while identifying key brain regions associated with particular functions provides a basis for localization of behaviour, it is well understood that brain function is distributed and that complex behaviours and traits arise through networks of interconnectivity (Bressler & Menon, 2010; Vinod Menon, 2013; Seitzman et al., 2019). Arithmetic is a complex behaviour, supported by an interconnected functional network that emerges across developmental time (for review: Peters & De Smedt, 2018). Key brain regions that emerged from the conjunction and contrast analyses of the current study (i.e., IPL, angular gyrus, inferior frontal gyrus) are known to have a central role in supporting integrated brain function and are often referred to as 'network hubs' (Oldham & Fornito, 2019). Activation within these brain regions has been linked to expertise in multiple cognitive domains across the lifespan (Bernardi et al., 2013; Binder et al., 2017; Grabner et al., 2006; Jeon & Friederici, 2017; Storti et al., 2019). Thus, the findings from the present study could also be interpreted as reflecting a distinction between problem types for which adults are typically 'experts' (i.e., retrieval problems) from arithmetic problems for which participants are not yet experts (i.e., procedural problems). Given that the human brain is a dynamic connectome rather than a set of localized modular regions, we propose that findings from the current study should be interpreted to reflect relative differences in the nodes of the network that support retrieval and procedural problem-solving strategies, rather than used to uncover specific localized modules.

5.4 | Development of arithmetic problem-solving

Our findings indicate that adults rely on both common and distinct brain regions when solving arithmetic problems associated with retrieval strategies compared to problems associated with procedural strategies. Critically, humans are not born with the ability to solve complex arithmetic problems. Considering major developmental trends in the emergence of arithmetic problem-solving is key in the study of arithmetic (for a review see: Peters & De Smedt, 2018). Individual neuroimaging studies have indicated that over the course of development children exhibit a shift from frontal to parietal regions (Rivera et al., 2005). This shift likely reflects children's transition away from procedural strategies and towards retrieval strategies. Notably, unlike adults, children do not exhibit greater activity in the angular gyrus for trained compared to untrained problems (Declercq et al., 2022). Currently, there are not enough empirical papers examining the neural correlates of arithmetic in children to conduct a meta-analysis examining neural correlates of retrieval and procedural arithmetic across developmental time. Once there are a sufficient number of empirical neuroimaging studies examining the neural correlates of arithmetic in children to conduct a meta-analysis, an exciting future study could examine whether the retrieval and procedural meta-analytic maps change across developmental time.

6 | CONCLUSION

Arithmetic problem-solving is a heterogeneous and complex skill. The present study used neuroimaging meta-analyses to reveal that arithmetic problems that are typically solved using retrieval compared to procedural strategies are supported by common brain regions in the bilateral intraparietal lobules as well as distinct brain regions. Retrieval problems specifically associate with convergent activation in the left angular gyrus; a region associated with fact retrieval, whereas procedural problems specifically associate with convergent activation in frontal regions involved in executive functioning, working memory, and mental manipulation. Broadly, findings from this study add to the growing body of literature uncovering the neural correlates of expertise across cognitive domains, as adults typically have more expertise with problems that they retrieve rather than calculate. In sum, the current meta-analysis extends our understanding of the complexities of the brain systems supporting arithmetic processing and motivates future research exploring mental arithmetic to consider arithmetic problems that are solved using retrieval and procedural strategies, independently and together.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available at through Sleuth, a BrainMap application (https://brainmap.org/sleuth/).

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