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Where arithmetic and phonology meet: The meta-analytic convergence of arithmetic and phonological processing in the brain

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ABSTRACT

Arithmetic facts can be solved using different strategies. Research suggests that some arithmetic problems, particularly those solved by fact retrieval, are related to phonological processing ability and elicit activity in left-lateralized brain regions that support phonological processing. However, it is unclear whether common brain regions support both retrieval-based arithmetic and phonological processing, and if these regions differ across children and adults. This study used activation likelihood estimation to investigate functional neural overlap between arithmetic and phonological processing, separately for children and adults. The meta-analyses in children showed six clusters of overlapping activation concentrated in bilateral frontal regions and in the left fusiform gyrus. The meta-analyses in adults yielded two clusters of concordant activity, one in the left inferior frontal gyrus and one in the left inferior parietal lobule. A qualitative comparison across the two age groups suggests that children show more bilateral and diffuse activation than adults, which may reflect attentional processes that support more effortful processing in children. The present meta-analyses contribute novel insights into the relationship between retrieval-based arithmetic and phonological processing in the brain across children and adults, and brain regions that may support processing of more complex symbolic representations, such as arithmetic facts and words.

1. Introduction

Arithmetic facts can be solved using different strategies, such as by calculation or retrieving an answer from memory. Small addition and multiplication problems are thought to be solved using direct memory retrieval, whereas subtraction problems are thought to be solved by calculation (Barrouillet et al., 2008; Campbell and Xue, 2001; Dehaene et al., 2003; Siegler, 1988). Retrieval-based arithmetic facts are learned using verbal strategies, are assumed to be stored as verbal codes (Dehaene et al., 2003), and are related to cognitive and neural processes that involve language, including phonological processing. The present study concerns concordant brain activity that supports retrieval-based arithmetic and phonological processing in children and adults.

Broadly, phonological processing encompasses three different sub-processes: phonological awareness, phonological memory, and rapid naming (e.g., De Smedt and Boets, 2010; Hecht et al., 2001; Torgesen et al., 1994). However, studies investigating the neural correlates of phonological processing (e.g., Bitan et al., 2007; Katzir et al., 2005; Tan et al., 2005) or the overlap between arithmetic and phonological processing in the brain (e.g., Andin et al., 2015; Passolunghi et al., 2007; Prado et al., 2011) typically employ tasks such as rhyme judgments, syllable decisions, and phonemic segmentation. These tasks, which necessitate the active analysis or manipulation of speech sounds within words rather than just the recall or retrieval of sounds (unlike sole phonological memory or rapid naming), align most closely with the sub-process of phonological awareness. The present analysis operationalizes phonological processing in accordance with this prior literature. Pseudoword reading tasks are also often used to investigate phonological processing because they involve the transformation of visual word forms to phonology independently of lexical meaning, utilizing a sublexical pathway of accessing phonology rather than the recognition of known words (e.g., Dietz et al., 2005; Georgiewa et al., 1999). Therefore, the present analysis also includes studies that use pseudoword reading tasks.

Evidence suggests that arithmetic and phonological processing are

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related across development. Phonological awareness is associated with arithmetic ability for children just entering school (Simmons et al., 2008), and with upper elementary school children's performance on small[3] arithmetic problems and those likely solved using retrieval (De Smedt et al., 2010). In adults, phonological processing is positively correlated with multiplication fact retrieval (De Smedt and Boets, 2010) and can interfere with multiplication ability (Lee and Kang, 2002). Further, phonological processing impairments (e.g., dyslexia) are related to arithmetic fact retrieval difficulty in children (Simmons and Singleton, 2008) and adults (De Smedt and Boets, 2010). Taken together, behavioral research suggests that phonological processing is related to performance on arithmetic problems that are likely retrieved from memory (e.g., small, addition and multiplication problems).

Evidence suggests a relationship between arithmetic and phonological processing at the neural level as well. Arithmetic problem solving associated with fact retrieval, such as small addition and multiplication problems, engages brain regions associated with language processing (i.e., angular gyrus [AG], superior temporal gyrus [STG], or middle temporal gyrus [MTG]) (Arsalidou and Taylor, 2011; Dehaene et al., 2003; Evans et al., 2014; Prado et al., 2014). Over development, left-lateralized brain regions, including those that relate to language, become increasingly recruited to support arithmetic processing (Ansari, 2008; Zamarian et al., 2009). For example, in a study of second to seventh graders, Prado et al. (2014) showed that children in higher grades had greater activation in left MTG for single-digit multiplication processing compared to children in lower grades. The authors found that the grade-related change in activity was greater for smaller versus larger multiplication problems (e.g., $3 \times 4 = 12$ versus $6 \times 7 = 42$). The relationship between arithmetic and phonological processing also extends to atypical development. Children with dyslexia show atypical brain activation in left temporoparietal areas during addition compared to their typically developing peers (Evans et al., 2014).

Further, neuroimaging in adults has consistently shown that arithmetic processing recruits left-lateralized brain regions involved in phonological processing. Several arithmetic studies have implicated the left AG (for a review see Zamarian et al., 2009), which is also involved in phonological processing and word meaning (Booth et al., 2004; Price, 2000). This region has shown greater activity for exact addition compared to approximate addition (Dehaene et al., 1999) and for more difficult compared to less difficult multiplication problems (Grabner et al., 2013). The left AG is thought to support efficient retrieval of overlearned arithmetic problems in adults (Delazer et al., 2003, 2005; Grabner et al., 2007, 2009a, 2009b; Ischebeck et al., 2006; Stanescu-Cosson et al., 2000; Tschentscher and Hauk, 2014; but also see Rosenberg-Lee et al., 2011). Arithmetic processing for retrieval-based facts in adults may recruit additional left-lateralized frontal and temporal brain structures that are involved in verbal processing, including the inferior frontal gyrus (IFG), STG, and MTG (Prado et al., 2011; Zhou et al., 2007). Across children and adults, research suggests that retrieval-based arithmetic problems likely recruit left-lateralized brain areas, and that activation in these areas is driven by increased fluency with arithmetic facts that occurs with learning.

However, even if arithmetic and phonological processing both recruit left-lateralized brain areas, specific areas that support these two processes may be regionally differentiated. The few studies that have examined direct neural overlap between arithmetic and phonological processing have been done in adults and have yielded conflicting results. Simon et al. (2002) investigated neural overlap in adults for calculation and phonological processing tasks and found a region in left intraparietal sulcus (IPS) mesial to the AG that was active for both tasks. However, Andin et al. (2015) found that multiplication tasks recruited posterior AG (i.e., PGp) while phonological processing recruited anterior left AG (i.e., PGa).

Taken together, the behavioral and neuroimaging research show a relationship between the cognitive and neural mechanisms that support retrieval-based arithmetic and phonological processing. Yet, few neuroimaging studies have examined this in children, and as illustrated above, more research is needed to inform whether common brain regions support both arithmetic and phonological processing in adults. Examining this relationship in children can provide first insight into brain regions that support both processes, shedding light on the extant behavioral relationship. Additionally, examining brain regions that support both arithmetic and phonological processing in adults can speak to the conflicting findings in the literature.

2. The present study

In the present study, we examine the convergence of brain regions that show reliable activity across arithmetic and phonological processing, separately in children and adults, using neuroimaging meta-analysis. We first conduct individual meta-analyses that identify concordant areas of activation across a set of empirical studies for each domain and age group. Second, we conduct conjunction analyses that identify areas of concordant activity across arithmetic and phonological processing, separately for each age group. We then qualitatively compare clusters common to arithmetic and phonological processing across the developmental and adult samples. For the developmental sample, we expect clusters of reliable activation in prefrontal regions, reflecting domain-general attention-related processes necessary for solving arithmetic problems or completing phonological tasks. Based on the behavioral relationship between arithmetic and phonological processing across development, we speculate there may be clusters of reliable activation in temporoparietal cortex (i.e., AG, STG, MTG) that reflect engagement of verbal representations. Alternatively, there may not be clusters in this area, in line with a developmental frontal-temporoparietal shift in brain regions that support arithmetic (e.g., Prado et al., 2014). For adults, we expect clusters of reliable activity in prefrontal areas, as above, and in left temporoparietal areas (i.e., AG, STG, MTG), reflecting fluent arithmetic fact retrieval and phonological processing. Alternatively, there may be temporoparietal clusters for arithmetic and phonological processing, but no shared clusters due to regional differentiation (e.g., Andin et al., 2015). Due to the lack of research on concordant brain activity for arithmetic and phonological processing in children, the qualitative comparison of the conjunction analyses is exploratory.

3. Methods

3.1. Literature search and article selection

There were four literature searches, one for each age group (i.e., developmental, adult) and domain (i.e., arithmetic, phonological processing). Each search followed the same two-step process: (1) a search of the PUBMED database and (2) a review of the reference sections of relevant papers for the specified meta-analyses. For brevity, we discuss searches and inclusion-exclusion criteria by domain, rather than age group.

3.1.1. Arithmetic processing

For the developmental sample, we conducted an initial search using the terms "fMRI and arithmetic and (child* or adolescen* or student)," which yielded 113 papers. For the adult sample, the initial search with the search terms "fMRI and arithmetic" yielded 306 papers. In both cases, we included studies published in English that used fMRI and visually-presented stimuli, studies that involved typically-developing

[3] For addition and multiplication, De Smedt et al. (2010) defined small problems as problems in which the product of the operands is less than or equal to 25. Small subtraction and division problems were the inverse of the small addition and multiplication problems.

Table 1
Number of studies, experiments, foci, and participants for each meta-analysis.

	Studies	Experiments	Foci	Participants
Developmental				
Arithmetic	16	17	168	530
Phonological processing	16	17	188	356
Adult				
Arithmetic	22	22	285	401
Phonological processing	23	23	237	363

participants, conducted whole brain analyses, and reported within-group contrasts between arithmetic processing and baseline conditions in standard Talairach or Montreal Neurological Institute (MNI) space. We included arithmetic processing tasks thought to draw on verbal strategies: single-digit addition and multiplication, small versus large problems (e.g., De Smedt et al., 2011), or retrieval (e.g., De Visscher et al., 2015), as well as studies with mixed arithmetic that included addition or multiplication (e.g., Andres et al., 2012; Price et al., 2013). Studies with participants under 18 were in the developmental meta-analysis and studies with participants over 18 were in the adult meta-analysis. We excluded reviews, clinical trials, case studies, and other meta-analyses. However, we checked the latter (Arsalidou and Taylor, 2011; Kaufmann et al., 2011) for additional potential studies. We also excluded studies with non-symbolic, non-arithmetic, or calculation-focused experimental tasks (e.g., subtraction or two-digit multiplication), and studies with aggregated analyses across children and adults. Table 1, rows 2 and 5, provides the final number of studies, experiments, foci, and participants for each analysis. One arithmetic study (Chen et al., 2006) contributed contrasts for two groups, yielding 17 experiments across the 16 studies in the developmental sample.

3.1.2. Phonological processing

Search terms were selected to capture the operationalization of phonological processing aligned with the literature discussed above. The search phrase for the developmental meta-analysis “fMRI and phono* and (processing or awareness) and (child* or adolescen* or student),” yielded 274 papers. Search terms for the adult meta-analysis were “fMRI and phono* and (processing or awareness)” and yielded 761 papers. For both searches, we included studies published in English that used fMRI and visually-presented tasks, that involved typically-developing participants, conducted whole brain analyses, and reported within-group contrasts involving a phonological processing task and a

Table 2
Details of the studies in the developmental meta-analyses, including sample size, mean age, contrast, and statistical threshold.

Study	Reference	*N*	Mean age	Contrast	Statistical threshold
Arithmetic					
A1	Davis et al. (2009a)	24	8.1 years	Addition > Greek letter matching	$p < 0.001$ uncorrected
A2	Davis et al. (2009b)	19	8.1 years	Addition > Greek letter matching	$p < 0.001$ uncorrected
A3	Meintjes et al. (2010)	16	10.5 years	Addition > Greek letter matching	$p < 0.05$ FDR
A4	Kucian et al. (2006)	10 (3rd grade) 10 (6th grade)	9.2 years 12.0 years	Exact addition > Approximate addition Addition > Grayscale matching	$p < .005$ FDR
A5	Cho et al. (2011)	103	7–9.9 years	Addition with retrieval > Addition with counting	$p < .01$ FWE
A6	Rosenberg-Lee et al. (2015)	20	8.44 years	Addition > Subtraction	$p < .01$ cluster-wise
A7	Ashkenazi et al. (2012)	17	97.41 months	Complex addition > Simple addition	$p < .01$ FWE
A8	Metcalfe et al. (2013)	74	7.8 years	Complex addition > Simple addition	$p < 0.01$ uncorrected; $p < 0.05$ FWE
A9	Rosenberg-Lee et al. (2015)	45 (2nd grade) 45 (3rd grade)	7.67 years 8.67 years	Complex addition > Simple addition	$p < 0.01$ FWE
A10	Demir et al. (2014)	40	10.9 years	Multiplication > Fixation	$p < .05$ cluster-wise
A11	Kawashima et al. (2004)	8	11.6 years	Multiplication > Fixation Addition > Fixation	$p < .05$ corrected
A12	Kesler et al. (2006)	15	14.6 years	Mixed addition and subtraction > Digit strings	corrected (unspecified)
A13	Rivera et al. (2002)	16	16.97 years	Mixed addition and subtraction > Digit strings	$p < .01$ cluster-wise
A14	Price et al. (2013)	33	17 years, 11.5 months	Mixed addition and subtraction > Digit matching	$p < .05$ FDR
A15	De Smedt et al. (2011)	18	11.77 years	Small addition/subtraction > Large addition/subtraction Addition > Subtraction	$p < .001$voxel-wise; $p < .05$ cluster-wise
A16	Chen et al. (2006)	8 (abacus experts) 8 (non-experts)	11.75 years 12.29 years	Serial addition > Viewing numbers	$p < .0001$ uncorrected
Phonological processing					
P1	Booth et al. (2004)	16	10.7 years	Rhyme judgment (words) > Visual matching	$p < .01$ corrected
P2	Booth et al. (2001)	5	11.1 years	Rhyme judgment (words) > Visual matching	$p < .001$ uncorrected
P3	Temple et al. (2001)	15	10.5 years	Rhyme judgment (letters) > Letter matching	$p < .025$ corrected
P4	Bitan et al. (2007)	36	11.7 years	Rhyme judgment (words) > Fixation	$p < .0001$ uncorrected; $p < .05$ corrected
P5	Cao et al. (2008)	12	12.3 years	Rhyme judgment (words) > Fixation	$p < .001$ uncorrected
P6	Hoeft et al. (2007)	64	10 years	Rhyme judgment (words) > Fixation	$p < .01$ FDR
P7	Hoeft et al. (2006)	10 (5th grade) 10 (3rd grade)	10.95 years 8.75 years	Rhyme judgment (words) > Fixation	$p < .001$ uncorrected
P8	Cao et al. (2006)	14	11.5 years	Rhyme judgment (words) > Fixation	$p < .001$ uncorrected
P9	McNorgan et al. (2011)	14 (young group) 12 (older group)	9.3 years 13.5 years	Rhyme judgment (words) > Fixation	$p < .05$ FDR
P10	Backes et al. (2002)	8	11.6 years	Rhyme judgment (pseudowords) > Fixation	$p < .05$ cluster-wise
P11	Georgiewa et al. (1999)	17	14.4 years	Pseudoword reading > Font strings	$p < .05$
P12	van der Mark et al. (2009)	24	11.3 years	Pseudoword reading > Fixation	$p < .05$ FDR
P13	Noble et al. (2006)	38	7 years, 11 months	Pseudoword one-back task > Fixation	$p < .0001$ uncorrected
P14	Yamada et al. (2011)	7	5.7 years	Letter one-back task > False fonts one-back task	$p < .05$ uncorrected
P15	Bach et al. (2010)	18	8.3 years	Different letter substitution > Same letter substitution Letter substitution > null	$p < .005$ cluster extent threshold
P16	Bach et al. (2013)	19	6.4 years	Word decoding > Symbol identification Word decoding > Null	$p < .005$ cluster extent threshold

baseline condition. Studies with participants under 18 were in the developmental meta-analysis and studies with participants 18 and over were in the adult meta-analysis. We excluded reviews, clinical trials, case studies, and other meta-analyses. We also excluded studies that did not meet the criteria for phonological processing (e.g., semantic judgments, word reading, rapid naming, verbal short-term memory) and studies involving non-alphabetic language tasks. However, we included two papers (Bach et al., 2013; Yamada et al., 2011) in the developmental meta-analysis that employed reading and decoding tasks with Kindergarteners, since beginning readers would need to utilize phonological processing during these tasks. We also excluded two papers from the phonological processing meta-analyses (Bitan et al., 2009; Kareken et al., 2000) that duplicated samples and contrasts from other included papers (Bitan et al., 2007; Lurito et al., 2000; respectively). In addition, we included five studies from our prior reading meta-analyses on reading in typical and atypical readers (Ashby and Pollack, 2016; Pollack et al., 2015; Pollack and Ashby, 2016) that met the inclusion criteria. Rows 3 and 6 in Table 1 provide the number of studies, experiments, foci, and participants. One phonological processing study (Hoeft et al., 2006), reported contrasts for two control groups, yielding 17 experiments across the 16 studies in the developmental sample.

3.1.3. Study overviews by age group

Table 2 presents an overview of the developmental arithmetic (Panel A) and developmental phonological processing (Panel B) studies, including sample size, mean age of participants, contrasts, and statistical thresholds. In line with recent meta-analyses (Sokolowski et al., 2017), we included all applicable contrasts per experiment (see Turkeltaub et al., 2012). For arithmetic, 13 studies (A1-A9, A11, A15, A16) involved single-digit addition. Participants chose between incorrect and correct answers to addition problems, verified addition facts, or added single-digit numbers sequentially. For control tasks, participants matched Greek letters or grayscale patterns, solved simple addition problems of the form $x + 1 = y$, performed subtraction, or added quantities with non-retrieval approaches (e.g., using counting). Three of the studies (A12-A15) involved single-digit mixed addition and subtraction problems contrasted with performing a digit detection task, a digit matching task, or solving larger addition and subtraction problems. Two studies (A10 and A11) involved verifying multiplication facts, with fixation as the baseline. Almost all studies required a button press; two studies (A11 and A16) required mental calculation only. One study (A16) contributed two experiments because they reported contrasts for two separate participant groups. Note that two studies (A9, A4) report two age groups, but analyses were collapsed across groups.

For developmental phonological processing, 10 studies (P1-P10) used a rhyming task with pairs of words, pseudowords or letters, with symbol matching, letter matching, or fixation as a baseline. Three studies (P11-P13) utilized a pseudoword reading task, with viewing false font strings or fixation as a baseline. In one study (P14), participants decided whether a letter was the same as a previously presented letter, and performed a similar baseline task using false fonts. In one study (P15) participants read words or pseudowords, mentally substituted a different letter, and decided whether the new word was a real word, making same-letter substitutions during the control condition. In another study (P16), Kindergarten-age participants decoded words; as a control task, they identified asterisks embedded in symbol strings. The participants produced responses by button press in all of the studies. One study (P7) reported contrasts separately for two control groups.

Table 3 presents an overview of the adult arithmetic (Panel A) and adult phonological processing (Panel B) studies including sample demographics, contrasts, and statistical thresholds. For arithmetic, nine studies (A1-A9) used single-digit addition experimental tasks. Baseline tasks were either approximate addition, non-symbolic addition, addition with digit or letter matching, holding digits in mind, number viewing, subtraction, or fixation. One study (A10) used mixed arithmetic operations presented serially, with fixation as a baseline. Two studies (A21-A22) involved mixed addition and subtraction items, with digit identification as a baseline. Ten studies (A11-A20) utilized multiplication tasks with baseline tasks that included digit matching, digit or letter identification, digit ordering, holding digits in mind, subtraction, division, or non-retrieval based multiplication. Most studies required a button press; three studies (A10, A19, A20) involved verbal report and two studies (A6, A13) involved mental calculation only.

For phonological processing, 14 studies (P1-P13, P23) utilized word or pseudoword rhyming. Baseline tasks for these studies included matching or detecting symbols, images, or letter case; matching word spelling; or thinking about word meaning commonalities. Five studies (P14-P18) used pseudoword reading contrasted with reading words, or viewing letter strings or line patterns. One study (P19) contrasted pseudoword and real word syllable counting, and one study (P20) contrasted final syllable matching with color matching. Another study (P21) contrasted matching initial sounds in words with matching objects. One study (P22) contrasted homophone judgments with words with fixation. Two studies (P4, P14) required a verbal response, five (P13, P15-P18) required silent reading, and the remainder required a button press.

3.2. Data analysis

3.2.1. Single-study meta-analyses

All analyses were done using GingerALE version 2.3.6 (Eickhoff et al., 2016, 2012, 2009; Turkeltaub et al., 2012). In light of recent recommendations put forth by Eickhoff et al. (2016), the current meta-analyses followed recommended guidelines for robust and reliable outcomes, which may reveal different patterns of results relative to analyses generated by previous GingerALE algorithms. Prior to analysis, all coordinates were converted into a common space; MNI coordinates were transformed into Talairach space (Talairach and Tournoux, 1988) using the *icbm2tal* transform native to GingerALE (Laird et al., 2010; Lancaster et al., 2007).

To conduct the analyses, ALE models the foci from each experiment as a three-dimensional Gaussian probability distribution (Eickhoff et al., 2009). It then generates three-dimensional activation maps by taking the maximum of each focus's Gaussian, a non-additive method that limits within-experiment effects (Turkeltaub et al., 2012). ALE then generates a null distribution for the ALE statistic and probabilities associated with the values of the activation maps (Research Imaging Institute UTHSCSA [RII], 2013). The probabilities can then be compared to the null distribution according to a chosen threshold. In this method, GingerALE simulates random data sets for a chosen number of permutations in which each data set retains the same properties as the original data, such as number of foci and subject sample sizes (RII, 2013). The simulated data is first thresholded with a cluster-forming threshold. Based on the distribution of the cluster sizes, the data are then subject to cluster-level thresholding, which sets a minimum volume cluster size (RII, 2013). The current analysis used 1000 permutations for the simulated data. Due to the two levels of thresholding, we employed the recommended cluster-forming threshold of uncorrected $p < .001$ with a cluster-level threshold of 0.05 (RII, 2013). GingerALE results were reported in Talairach space, displayed using the anatomical templates native to GingerALE, and were automatically labeled using the Talairach Daemon (talairach.org). We confirmed the labeling from GingerALE using the Talairach Daemon in Mango (RII, 2015) and found no differences.

3.2.2. Conjunction and subtraction analyses

Conjunction analyses (Eickhoff et al., 2011) determined areas of overlap between arithmetic and phonological processing, separately in the developmental and adult samples. ALE uses the meta-analytic results for arithmetic and phonological processing, and a third set of

Table 3
Details of the studies in the adult meta-analyses, including sample size, mean age, contrast, and statistical threshold.

Study	Reference	N	Mean age	Contrast	Statistical threshold
Arithmetic					
A1	Venkatraman et al. (2005)	10	20–25 years	Addition > Digit matching	$p < .001$ uncorrected; $p < .05$ corrected
A2	Stanescu-Cosson et al. (2000)	7	22–26 years	Exact addition > Approximate addition Addition > Letter matching	$p < .001$ uncorrected; $p < .05$ cluster-wise
A3	van der Ven et al. (2016)	23	21.04 years	Exact addition > Non-symbolic addition	$p < .001$ uncorrected; $p < .05$ FWE
A4	Gullick and Wolford (2014)	24	19 years, 10 months	Addition > Subtraction	$p < .001$ uncorrected; $p < .05$ FDR
A5	Hugdahl et al. (2004)	12	31.0 years	Addition > Digit identification	$p < .05$ corrected
A6	Kawashima et al. (2004)	8	44.1 years	Addition > Fixation Multiplication > Fixation	$p < .05$ corrected
A7	Zhou et al. (2007)	20	22.7 years	Addition > Fixation Multiplication > Fixation	$p < .001$ uncorrected
A8	Kuo et al. (2008)	12	21–29 years	Serial addition > Digit maintenance	$p < .001$ (unspecified)
A9	Sammer et al. (2007)	20	25.4 years	Serial addition > Viewing numbers	$p < .05$ FWE
A10	De Pisapia et al. (2006)	20	20.3 years	Serial arithmetic > Null	$p < .05$ uncorrected
A11	Ischebeck et al. (2006)	12	26.8 years	Multiplication > Digit matching	$p < .0001$ uncorrected; $p < .05$ corrected
A12	Delazer et al. (2003)	13	30.5 years	Multiplication > Digit matching	$p < .0001$ uncorrected
A13	Chochon et al. (1999)	8	20–30 years	Multiplication > Digit ordering Multiplication > Digit identification	$p < .001$ uncorrected; $p < .05$ corrected
A14	Andin et al. (2015)	17	28.6 years	Multiplication > Digit ordering Multiplication > Letter identification	$p < .001$ uncorrected; $p < .05$ FWE
A15	Jost et al. (2009)	16	24.5 years	Multiplication > Digit maintenance Multiplication (retrieval) > Multiplication (non-retrieval)	$p < .001$ uncorrected
A16	De Visscher et al. (2015)	20	29 years	Multiplication (retrieval) > Multiplication (non-retrieval)	$p < .001$ uncorrected
A17	Rosenberg-Lee et al. (2011)	20	23.9 years	Multiplication > Subtraction Multiplication > Division Multiplication > Digit identification	$p < .01$ corrected
A18	Zarnhofer et al. (2012)	42	23 years	Multiplication > Subtraction Multiplication (digits) > Multiplication (number words)	$p < .001$ uncorrected; $p < .05$ FWE
A19	Andres et al. (2012)	18	21.3 years	Multiplication > Subtraction Mixed multiplication and subtraction > Letter identification	$p < .05$ FDR
A20	Andres et al. (2011)	10	21.0 years	Multiplication > Subtraction Mixed multiplication and subtraction > Letter identification	$p < .001$ uncorrected; $p < .05$ corrected
A21	Keller and Menon (2009)	49	23.99 years	Mixed addition and subtraction > Digit identification	$p < .01$ uncorrected $p < .001$ corrected;
A22	Menon et al. (2000)	16	20.28 years	Mixed addition and subtraction (3 operands) > Digit identification Mixed addition and subtraction (2 operands) > Digit identification	$p < .01$ uncorrected
Phonological processing					
P1	Geva et al. (2012)	12 19	24.6 years 64.1 years	Rhyme judgment (words) > Visual matching	$p < .05$ FWE
P2	Hernandez et al. (2013)	16	21.2 years	Rhyme judgment (words) > Visual matching	$p < .05$ clusterwise
P3	MacSweeney et al. (2009)	7	32 years, 7 months	Rhyme judgment (words) > Visual matching	$p < .05$ voxelwise; $p < .005$ clusterwise
P4	Pecini et al. (2008)	10	27.1 years	Rhyme judgment (words) > Visual matching	$p < .05$ corrected
P5	Booth et al. (2004)	16	25.2 years	Rhyme judgment (words) > Visual matching	$p < .01$ corrected
P6	Booth et al. (2003)	15	25.8 years	Rhyme judgment (words) > Visual matching	$p < .001$ uncorrected
P7	Booth et al. (2001)	4	25.5 years	Rhyme judgment (words) > Visual matching	$p < .001$ uncorrected
P8	Poldrack et al. (2001)	8	20–29 years	Rhyme judgment (words) > Visual matching	$p < .001$ uncorrected
P9	Lurito et al. (2000)	5	27 years	Rhyme judgment (words) > Visual matching	$t > 6$, uncorrected
P10	Cousin et al. (2006)	11	27.5 years	Rhyme judgment (words) > Visual detection	$p < .001$ uncorrected
P11	Oron et al. (2016)	37	46.3 years	Rhyme judgment (words) > Visual detection	$p < .05$ FWE
P12	Booth et al. (2002)	13	24.6 years	Rhyme judgment (words) > Word spelling matching	$p < .001$ uncorrected
P13	McDermott et al. (2003)	20	22.1 years	Rhyme processing (words, silent) > Semantic processing	$p < .0012$ voxelwise
P14	Taylor et al. (2014)	22	18–20 years	Pseudoword reading > Word reading	$p < .001$ uncorrected; $p < .05$ FWE
P15	Mechelli et al. (2005)	22	36 years	Pseudoword reading (silent) > Word reading	$p < .05$ corrected
P16	Dietz et al. (2005)	16	31.1 years	Pseudoword reading (silent) > Word reading	$p < .001$ uncorrected
P17	Joubert et al. (2004)	10	26 years	Pseudoword reading (silent) > Viewing letter strings	$p < .0005$ voxelwise
P18	Danelli et al. (2013)	28	21 years	Pseudoword reading (silent) > Viewing line patterns	$p < .05$ FWE
P19	Clark and Wagner (2003)	20	18–33 years	Syllable counting (pseudowords) > Syllable counting (words)	$p < .001$ uncorrected
P20	Rudner et al. (2013)	20	26.4 years	Final syllable two-back task > Color two-back task	$p < .001$ uncorrected; $p < .05$ corrected
P21	Katzir et al. (2005)	12	18–25 years	Initial sound matching > Object matching	$p < .001$ uncorrected
P22	Tham et al. (2005)	6	18–23 years	Homophone judgment > Fixation	$p < .05$ uncorrected
P23	Burton et al. (2005)	14	26.7 years	Rhyme judgment (words/pseudowords) > Visual matching	$p < .01$ uncorrected; $p < .05$ corrected

Table 4
Activation likelihood estimation results for arithmetic and phonological processing, and the conjunction analysis in the developmental sample, including cluster, Talairach coordinate, ALE value, volume, and contributing studies. Local extrema are italicized.

Cluster	Talairach coordinates			ALE value	Volume (mm^3)	Contributing studies
	x	*y*	*z*			
(A) Arithmetic processing						
Left Superior Frontal Gyrus (BA 6)	−2	8	52	0.020871	2400	A1, A2, A3, A7, A9, A11, A14, A13, A16
Right Cingulate Gyrus (BA 32)	4	20	42	0.020135		
Right Insula (BA 13)	32	18	6	0.036845	2208	A1, A2, A3, A4, A8, A9, A13, A14
Left Insula (BA 13)	−30	18	6	0.030595	1800	A4, A5, A7, A8, A9, A14
Left Inferior Frontal Gyrus (BA 46)	−34	32	10	0.016215		
Left Precentral Gyrus (BA 6)	−46	−2	36	0.017363	800	A4, A10, A11, A13, A14,
Left Fusiform Gyrus (BA 37)	−46	−56	−14	0.018369	664	A4, A11, A12, A13
(B) Phonological processing						
Left Inferior Frontal Gyrus (BA 6)	−44	2	32	0.022825934	2160	P2, P5, P6, P7, P8, P9, P12, P13
Left Inferior Frontal Gyrus (BA 9)	−52	12	32	0.01523793		
Left Superior Frontal Gyrus (BA 6)	−6	8	50	0.023172587	1904	P4, P5, P6, P7, P8, P12, P16
Left Middle Temporal Gyrus (BA 22)	−52	−38	2	0.023622176	1640	P1, P2, P4, P8, P9, P10, P14, P16
Left Fusiform Gyrus (BA 37)	−42	−50	−14	0.023692332	1624	P1, P5, P7, P8, P9, P12, P13
Right Insula (BA 13)	34	22	4	0.018411051	1056	P4, P7, P8, P9, P14
Right Inferior Frontal Gyrus (BA 47)	34	22	−8	0.014701883		
Left Inferior Frontal Gyrus (BA 46)	−44	26	14	0.022119224	960	P1, P4, P5, P8
(C) Conjunction of Arithmetic and Phonological Processing						
Left Superior Frontal Gyrus (BA 6)	−2	8	52	0.020871054	720	A9, A14, A16, P7, P12
Left Precentral Gyrus (BA 6)	−46	0	36	0.017064271	568	A4, A10, A11, A14, P8, P12, P13
Right Insula (BA 13)	34	22	4	0.018411051	488	A13, A14, P4, P7, P8, P9
Left Fusiform Gyrus (BA 37)	−46	−54	−14	0.015494634	184	A12
Right Superior Frontal Gyrus (BA 6)	6	12	48	0.011203893	8	*None*
Right Superior Frontal Gyrus (BA 6)	8	14	48	0.01048557	8	*None*

results from the pooled foci from the arithmetic and phonological processing studies acting as an empirical baseline or "null" distribution. The present analysis meets the criterion for adequate power, which is 17–20 experiments for each single-study meta-analysis (Eickhoff et al., 2016; Eickhoff and Etkin, 2016). To determine areas of overlap across the two meta-analyses, GingerALE creates a new ALE map that takes the voxel-wise minimum value from the two original thresholded maps (RII, 2013).

As part of the conjunction analysis, ALE provides subtraction analyses that directly contrast the single-file maps. To calculate significance, GingerALE creates ALE images from randomized simulated data, subtracts the images, and compares them to the real data. This process is iterated to produce p-value images and image statistics that are reported in z-score values (RII, 2013). The current analysis used 5000 permutations with thresholding at $p < .01$ uncorrected. Because our focus is on regions of overlap in children and adults, we include the subtraction results as supplemental material.

4. Results

4.1. Developmental sample

Table 4 displays the results of the three developmental meta-analyses including the cluster location, Talairach coordinates, ALE values, cluster size in mm^3, and contributing studies. Panel A displays the single-study meta-analysis for arithmetic processing. Five clusters show reliable activation when participants engage in arithmetic tasks, four of them in frontal regions. The largest cluster is in the left superior frontal gyrus (SFG) (BA 6) with a local extremum in the right cingulate gyrus (BA 32). The second cluster is in the right insula (BA 13). Neighboring gray matter (i.e., within ± 5 mm) to this cluster includes the right claustrum (704 mm^3) and the right IFG (56 mm^3, BA 45; 48 mm^3, BA 13), which suggests this cluster is in anterior right insula. The third cluster is in the left insula (BA 13) with a local extremum in the left IFG (BA 46). Neighboring gray matter outside of the left insula includes the left claustrum (520 mm^3) and the left IFG (216 mm^3, BA 46; 192 mm^3, BA 45), which suggests this cluster is in anterior left insula. The fourth cluster is in the left precentral gyrus (BA 6) and the fifth is in left fusiform gyrus (FFG) (BA 37). Fig. 1 displays the clusters from the arithmetic meta-analysis in red.

Panel B in Table 4 displays the results of the phonological processing meta-analysis. Six clusters show reliable activation across studies. Clusters are in mostly left-lateralized frontal, temporal, and temporo-occipital regions. The largest cluster is in the left IFG (BA 6), with a local extremum in the left IFG (BA 9). The second cluster is in the left SFG (BA 6). The third and fourth clusters are in the left MTG (BA 22) and left FFG (BA 37), respectively. The fifth cluster is in the right insula (BA 13) with a local extremum in the right IFG (BA 47). Neighboring gray matter in the right IFG (280 mm^3, BA 47; 152 mm^3 BA 45) suggests this cluster is in anterior right insula. The last cluster is in the left IFG (BA 46). Fig. 1 shows the clusters from the phonological processing meta-analysis in blue.

Panel C in Table 4 presents the results of the conjunction analysis, which quantitatively assesses clusters of concordant activation for arithmetic and phonological processing tasks. There are six clusters of reliable activation, five that are in frontal areas. The largest cluster is in the left SFG (BA 6). The second cluster is in the left precentral gyrus (BA 6). The third cluster is in the right insula (BA 13). Neighboring gray matter outside of the insula includes the right claustrum (72 mm^3) and right IFG (40 mm^3, BA 45; 24 mm^3, BA 13), which suggests this cluster is in anterior right insula. The fourth cluster is in left FFG (BA 37). The fifth and sixth clusters are both in right SFG (BA 6). Even though these clusters have no listed contributing studies (see Table 4, last two rows), they still produce reliable activation across studies. This is because contributing studies have coordinates inside the boundary of the cluster, but additional studies may contribute coordinates that lie on or just outside of the cluster boundary (RII, 2013). Note there is no right SFG cluster per se in the phonological processing meta-analysis (see Table 4). Rather, the cluster in left SFG has neighboring gray matter in the right SFG (424 mm^3, BA 6). Fig. 1 displays the clusters from the conjunction analysis in green. We provide the subtraction analyses in Table S1 in the supplemental material.

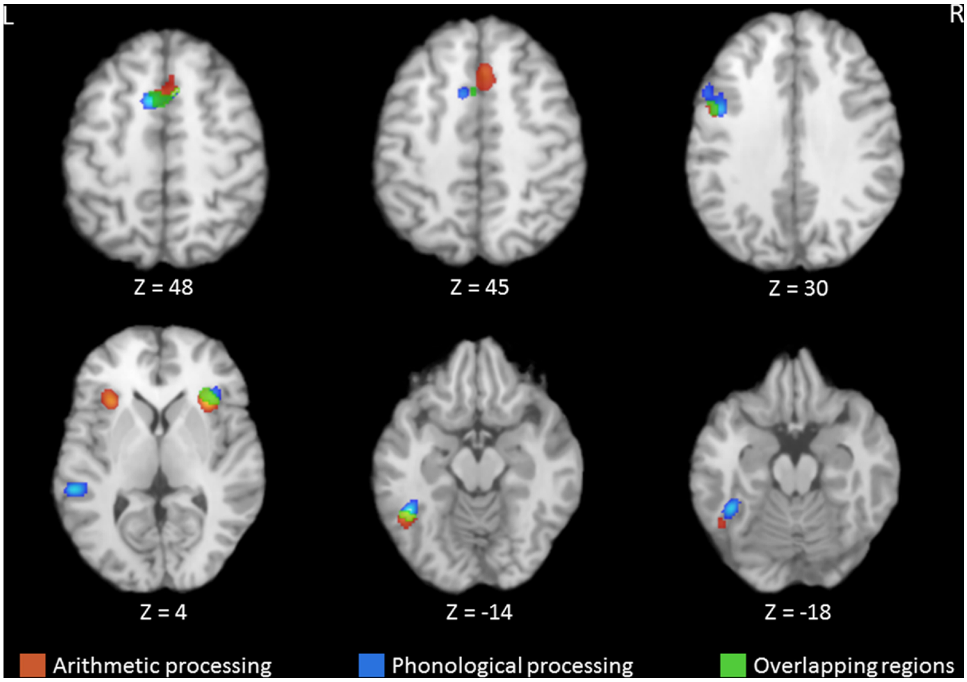

Fig. 1. Selection of axial slices showing clusters with significant activation from the arithmetic processing meta-analysis (red), phonological processing meta-analysis (blue), and the conjunction analysis (green) for the developmental sample.

4.2. Adult sample

Table 5 displays the results of the three adult meta-analyses. Panel A displays the single-study meta-analysis for arithmetic processing. Six clusters show reliable activation across frontal and parietal regions. The largest cluster is in the left precuneus (BA 19) with local extrema in the precuneus (BA 7), left angular gyrus (BA 39), and left superior parietal lobule (BA 7). The second cluster is in the left inferior frontal gyrus (BA 9). The third cluster is in right precuneus (BA 19) with local extrema in the right precuneus (BA 7) and right superior parietal lobule (BA 7). The fourth cluster is in right insula (BA 13) and has neighboring gray matter in the right claustrum (184 mm^3) and right IFG (96 mm^3, BA 47; 72 mm^3, BA 45), which suggests this cluster is in anterior insula. The fifth cluster is in the right inferior parietal lobule (IPL) (BA 40). The final cluster is in the left insula (BA 13) with a local extremum in left IFG (BA 47), which suggests this cluster is in anterior insula. Fig. 2 shows these six clusters in red.

Panel B of Table 5 displays the clusters resulting from the phonological processing meta-analysis. There are four clusters of reliable activation spanning left lateralized frontal, temporal, and parietal regions. The largest cluster is in left IFG (BA 6) with eight left-lateralized local extrema (see Table 5, rows 15–22). These include IFG (BA 46, BA 44, BA 10), middle frontal gyrus (BA 46, BA 9), and STG (BA 22). The second cluster is in the left IPL (BA 7) and contains local extrema in the left precuneus (BA 19) and left AG (BA 39). The third and fourth clusters are in the left culmen and the left SFG (BA 6), respectively. Fig. 2 displays these clusters in blue.

Table 5 Panel C displays clusters from the conjunction analysis of arithmetic and phonological processing in adults. There are two clusters of overlapping activity. The first is in the left IPL (BA 7) with local extrema in the left precuneus (BA 19) and left AG (BA 39). Additional neighboring gray matter includes the superior parietal lobule (1128 mm^3, BA 7) and IPL (48 mm^3, BA 40; 40 mm^3, BA 39). The second cluster is in the left IFG (BA 9). We display these clusters in Fig. 2 in green. We provide results of the subtraction analyses for the adult sample in Table S2 of the supplemental material.

5. Discussion

The present study examined neural functional overlap for arithmetic and phonological processing in developmental and adult samples. For each age group, we conducted separate meta-analyses and a subsequent conjunction analysis. Each meta-analysis produced clusters that are reliably activated across studies. For each age group, we briefly discuss results for the individual meta-analyses. We focus on clusters common to both arithmetic and phonological processing and a qualitative comparison of the conjunction analyses across the two age groups.

5.1. Developmental sample

5.1.1. Single-study meta-analyses

The arithmetic meta-analysis yielded clusters in bilateral frontal and occipito-temporal regions that are in line with prior work on numerical and arithmetic processing. Prior meta-analyses of numerical abilities and arithmetic in children found reliable activation in bilateral insula, premotor cortex, left IFG, and inferior temporal gyrus (Kaufmann et al., 2011), and left superior frontal gyrus (Houdé et al., 2010). An arithmetic-specific role for anterior insula and the left SFG/right cingulate is unclear. Activity in these regions may relate to the insula-cingulate salience network associated with cognitive control that supports arithmetic processing (Menon, 2015; Supekar and Menon, 2012), or switching between the executive control and default mode networks (Craig, 2009; Menon and Uddin, 2010). Recruitment of frontal regions during arithmetic may reflect the role of attentional processes (Houdé et al., 2010; Owen et al., 2005). Indeed, children engage frontal regions more and temporoparietal regions less than adults, and this difference in activity reflects a developing fluency with arithmetic (Ansari, 2008; Rivera et al., 2005; Zamarian et al., 2009). This could also partially account for the absence of clusters in parietal and temporoparietal regions, which have been present in some meta-analyses with children (Kaufmann et al., 2011), but not others (Houdé et al., 2010). This discrepancy may be due to differences in study contrasts. For example, Kaufmann et al. (2011) was limited to seven

Table 5
Activation likelihood estimation results for arithmetic and phonological processing, and the conjunction analysis in the adult sample, including cluster, Talairach coordinate, ALE value, volume, and contributing studies. Local extrema are listed in italics.

Cluster	Talairach coordinates			ALE value	Volume (mm³)	Contributing studies
	x	y	z			
(A) Arithmetic processing						
Left Precuneus (BA 19)	−28	−72	34	0.04120283	5888	A1, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A17, A19, A20, A21, A22
Left Precuneus (BA 7)	−28	−64	38	0.02997227		
Left Angular Gyrus (BA 39)	−30	−58	38	0.029711127		
Left Superior Parietal Lobule (BA 7)	−32	−60	48	0.028536372		
Left Inferior Frontal Gyrus (BA 9)	−42	4	28	0.036799587	2488	A1, A6, A7, A12, A17, A20, A21, A22
Right Precuneus (BA 19)	28	−70	38	0.022211188	1808	A12, A7, A17, A19, A20, A21, A22
Right Precuneus (BA 7)	28	−68	34	0.020805586		
Right Superior Parietal Lobule (BA 7)	32	−54	40	0.015481527		
Right Insula (BA 13)	32	22	4	0.021382697	944	A7, A19, A20, A21, A22
Right Inferior Parietal Lobule (BA 40)	42	−42	42	0.020873273	904	A1, A9, A11, A19
Left Insula (BA 13)	−32	16	6	0.017058335	832	A7, A12, A18, A21
Left Inferior Frontal Gyrus (BA 47)	−32	20	−2	0.016205575		
(B) Phonological processing						
Left Inferior Frontal Gyrus (BA 6)	−44	2	32	0.03733236	12096	P1, P2, P3, P4, P5, P7, P8, P9, P10, P11, P13, P14, P15, P16, P17, P18, P19, P20, P21, P22
Left Middle Frontal Gyrus (BA 46)	−46	30	22	0.027697794		
Left Inferior Frontal Gyrus (BA 46)	−48	28	14	0.026974306		
Left Inferior Frontal Gyrus (BA 44)	−52	4	18	0.025123559		
Left Inferior Frontal Gyrus (BA 10)	−42	46	2	0.024867302		
Left Superior Temporal Gyrus (BA 22)	−50	12	0	0.024489433		
Left Middle Frontal Gyrus (BA 9)	−40	18	26	0.018028196		
Left Inferior Frontal Gyrus (BA 45)	−46	22	2	0.015826639		
Left Inferior Frontal Gyrus (BA 46)	−40	38	8	0.013467827		
Left Inferior Parietal Lobule (BA 7)	−32	−58	48	0.024964614	2888	P1, P5, P11, P13, P14, P16, P19, P22
Left Precuneus (BA 19)	−28	−66	40	0.01947619		
Left Angular Gyrus (BA 39)	−28	−60	36	0.017271489		
Left Culmen	−40	−52	−20	0.024182009	1112	P5, P6, P14, P18
Left Superior Frontal Gyrus (BA 6)	−2	8	50	0.020853365	960	P14, P17, P19, P21
(C) Conjunction of Arithmetic and Phonological Processing						
Left Inferior Parietal Lobule (BA 7)	−32	−58	48	0.024964614	2384	A1, A7, A9, A6, A13, A17, A19, A20, A21, P1, P11, P13, P14, P19, P22
Left Precuneus (BA 19)	−28	−66	40	0.01947619		
Left Angular Gyrus (BA 39)	−28	−60	36	0.017271489		
Left Inferior Frontal Gyrus (BA 9)	−44	6	28	0.03553766	2272	A1, A6, A7, A17, A20, A12, A21, A22, P1, P3, P4, P7, P9, P11, P14, P16, P18, P19, P22

studies (included in the present analysis); almost all involved contrasts with non-numeric baselines. The present analysis included a majority of contrasts with numeric or non-retrieval based baseline tasks (see Table 2), both of which would subtract out number specific activity. Because fluency with arithmetic retrieval increases over developmental time, children may not be fluent enough to reliably engage temporoparietal regions across studies.

The phonological processing meta-analysis produced clusters of reliable activation in left frontal, temporal, and occipital regions, in addition to the right anterior insula. These results are in line with models of reading and phonological processing in children that outline a left-lateralized fronto-temporo-occipital network (Houdé et al., 2010; Martin et al., 2015). Specifically, the clusters largely replicate a well-known network of left-lateralized brain regions for typical readers that includes the IFG, MTG, and FFG (Jobard et al., 2003; Sebastian et al., 2014; Vigneau et al., 2006). As mentioned above, activation in the insula could be due to attentional processes or shifting between attention and the default mode network (Craig, 2009; Menon and Uddin, 2010).

5.1.2. *Clusters common to arithmetic and phonological processing*

5.1.2.1. Left precentral and bilateral SFG. Four of the six clusters common to arithmetic and phonological processing were in left precentral gyrus and bilateral SFG. A prior meta-analysis in children showed reliable activation in left SFG for number abilities, but not reading (Houdé et al., 2010). Both regions were also found in a prior meta-analysis on calculation in children (Kaufmann et al., 2011). Reliable activation in these regions is likely driven by domain-general task demands. For example, activity in the SFG has been associated with selective attention (Anderson et al., 2007). The cluster in precentral gyrus could also reflect different levels of interference in generating motor responses for experimental and control tasks. For example, Kesler et al. (2006) contrasted judging the correctness of addition and subtraction facts (i.e, a true-false judgment) with pressing a button

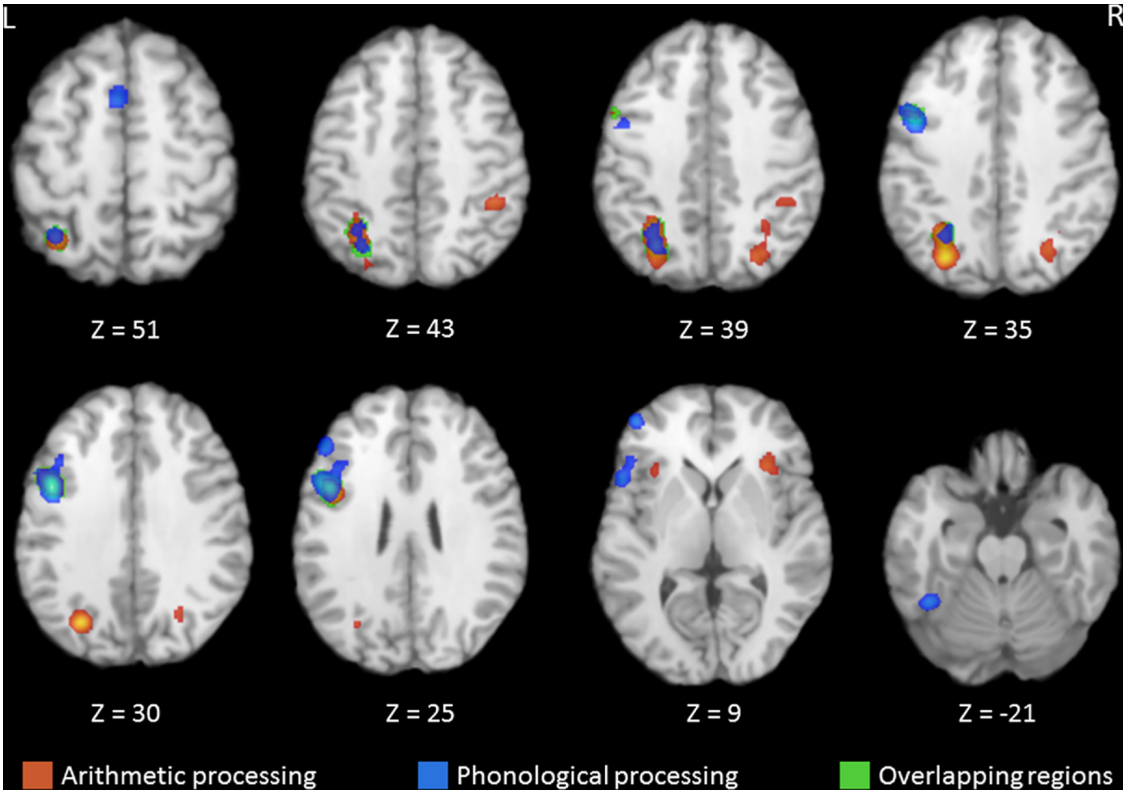

Fig. 2. Select axial slices showing clusters with significant activation from the arithmetic processing meta-analysis (red), phonological processing meta-analysis (blue), and the conjunction analysis (green) for the adult sample.

when a '0' was present (i.e., a go/no-go task).

5.1.2.2. Right insula. A cluster in the right anterior insula aligns with prior meta-analyses of number and arithmetic processing in children (Kaufmann et al., 2011). However, right insula activity is found in some reading meta-analyses in children (Houdé et al., 2010), but not others (Martin et al., 2015); this may be due in part to specific contrast selection criteria in prior studies (e.g., contrasts that isolate semantic processing). Reliable activation in the right insula has also been present in some meta-analyses of atypical reading development. Maisog et al. (2008) found hyperactivity in anterior insula for atypical readers, which may have been related to atypical readers' perception of reading-related stimuli as aversive. Barquero et al. (2014) found underactivation in right insula prior to a reading intervention with children, but found consistent activation in this region after intervention.

The role of the right anterior insula in numeracy or literacy, specifically, is currently unclear. Recruitment of this region may support arithmetic and phonological processing through domain-general functioning. Models of anterior insula function suggest that it supports higher level cognitive processing including task-related attentional capture and control (Craig, 2009; Menon and Uddin, 2010; Nelson et al., 2010), decision-making, or knowing information before recalling it (Craig, 2009). The insula is also thought to direct cognitive and neural resources to internally or externally focused attention (Menon and Uddin, 2010). In the present study, recruitment of the right anterior insula could represent the direction of externally focused task-specific attention toward arithmetic or phonological tasks or the experience of knowing the answer to an arithmetic fact or whether two words rhyme.

5.1.2.3. Left fusiform gyrus. The final cluster common to arithmetic and phonological processing is in the left FFG. Prior arithmetic meta-analyses either did not find activation near this region (Houdé et al., 2010) or showed a cluster in the neighboring inferior temporal gyrus (Kaufmann et al., 2011). Reliable activation in the left FFG or inferior temporal gyrus has also been found in prior meta-analyses related to typically-developing readers (Houdé et al., 2010; Martin et al., 2015; Pollack et al., 2015). This cluster may be common to arithmetic and phonological processing because of its functional role in symbol recognition for words and digits.

The left FFG houses the Visual Word Form Area (VWFA), an area situated near Talairach coordinates −42, −57, −12 that is consistently activated by letters and words (Cohen et al., 2000; Hannagan et al., 2015; McCandliss et al., 2003). Evidence suggests there may be a number form area (NFA) lateral to the VWFA, in (bilateral) ventral inferior temporal gyrus (Grotheer et al., 2016; Hannagan et al., 2015; Shum et al., 2013; however, see Peters et al. (2015) and Price and Ansari (2011) for an alternative view). Whether the left VWFA and NFA are separate or merged is unclear (Hannagan et al., 2015; Starrfelt and Behrmann, 2011). There appears to be functional specialization of both regions in adults compared to children (for reviews, see Menon, 2015; Schlaggar and McCandliss, 2007). Indeed, recent research looking across children and adults suggests that the VWFA and NFA may be merged in children and become functionally distinct areas in adulthood (Cantlon et al., 2011). Thus, it is plausible that the cluster in left FFG found in the present study supports symbolic processing for both number and letter/word identification.

5.2. Adult sample

5.2.1. Individual meta-analyses

The arithmetic analysis yielded clusters that span bilateral precuneus with local extrema in the left AG and bilateral superior parietal lobule. These results align with models of numerical cognition that characterize the superior parietal lobule as a key region for visual attention and number processing and characterize temporo-parietal regions including the AG that support fluent arithmetic fact retrieval (e.g., Dehaene et al., 2003; Zamarian et al., 2009). Additional clusters in frontal regions including bilateral insula and left IFG replicate prior meta-analytic findings in adults related to arithmetic (Arsalidou and Taylor, 2011) and support the notion that temporoparietal and frontal areas both support arithmetic fact retrieval (e.g., Jost et al., 2011).

The phonological processing meta-analysis produced left-lateralized clusters that span frontal regions including superior and inferior frontal gyri, the STG, and the IPL including the AG. Clusters in these regions align with the left-lateralized reading network in adults (Jobard et al., 2003) and specifically with regions known to support phonological processing in adults (Vigneau et al., 2006). Taken together, the results of the individual adult meta-analyses largely replicate well-established regions of brain activity that support arithmetic and phonological processing, respectively.

5.2.2. Clusters common to arithmetic and phonological processing

5.2.2.1. Left inferior parietal lobule. The first cluster common to arithmetic and phonological processing spans the left IPL including the AG. The AG has been implicated separately in fact retrieval (e.g., Grabner et al., 2009a) and phoneme discrimination (Turkeltaub and Coslett, 2010). Studies examining overlap in AG activation for arithmetic and phonological processing have produced inconsistent results. Simon et al. (2002) found shared activation mesial to the left AG for calculation and phoneme detection, but their task (subtraction) does not reflect fact retrieval. Andin et al. (2015) found regional differentiation in the AG for multiplication (i.e., PGp) and phonological processing (i.e., PGa). However, the results of the present meta-analysis support the notion that temporoparietal regions spanning the IPL and including the AG support both arithmetic and phonological processing in adults. Concordant activity in this region may reflect familiarity across symbol sets including letters and digits (Price and Ansari, 2011) or the role of this region as a hub for cross-modal integration (Seghier, 2013). Specifically, activity in the left IPL/AG cluster may support the connection of symbols (i.e., letters, words, and arithmetic facts) to their associated verbal representations.

5.2.2.2. Left IFG. The second cluster common to arithmetic and phonological processing was in left IFG. Prior studies that have investigated an overlap in arithmetic and phonological processing have shown mixed results related to left IFG activation. Andin et al. (2015) found that multiplication was associated with activity in the pars triangularis portion of left IFG (BA 45), whereas phonological processing was associated with posterior activity in the pars opercularis portion of left IFG (BA 44). Similarly, Fedorenko et al. (2012) found an area on the border of BA 44/45 active for language-specific tasks, with brain activity in both anterior and posterior regions bordering BA 44/45 responding to various tasks, including mental arithmetic. Simon et al. (2002) found a common area of activation in left IFG for subtraction and phoneme detection tasks, however this area was also common to other tasks (i.e., grasping). Taken together, these studies do not provide evidence of overlapping brain activation in left IFG that supports retrieval-based arithmetic and phonological processing. However, the results of the current meta-analysis suggest there may be.

One reason for this discrepancy may be a lack of anatomical specificity across studies, as illustrated above. The discrepancy could also be due to variation in tasks across studies. Tasks that place more demands on working memory may be associated with higher left IFG activity. Evidence suggests that arithmetic fact difficulty may vary by operation (Zhou et al., 2007) or by strategy choice (Tschentscher and Hauk, 2014). While the arithmetic problems chosen for the present analysis are thought to rely on retrieval, only a few imaging studies to date explicitly account for strategy choice (e.g., De Visscher et al., 2015; Grabner et al., 2009a; Jost et al., 2009).

5.3. A comparison of overlap of activation across groups

A qualitative comparison of the developmental and adult conjunction analyses shows that there were no common clusters of brain activity that support both arithmetic and phonological processing across the two age groups. The conjunction analyses for both children and adults did reveal clusters in frontal regions. However, for children clusters were in bilateral SFG, left precentral gyrus, and right insula, while for adults there was one cluster in left IFG. This comparison illustrates more diffuse and bilateral concordant activation concentrated in frontal regions for the developmental sample compared to adults. This may reflect children's greater reliance on domain general processes such as working memory and attention than adults as children develop fluency with arithmetic and phonological processing tasks. Research suggests that across development, reading is associated with an increase in brain activity in left-lateralized frontal and temporal areas, such as IFG, and a decrease in activity in right-lateralized regions (Turkeltaub et al., 2003). Similarly, brain regions that support arithmetic shift over development, reflecting an increase in recruitment of temporal and parietal regions as children become more fluent with arithmetic such as multiplication facts (Prado et al., 2014; Zamarian et al., 2009). The lack of a left temporoparietal cluster in the developmental sample is likely due to absence of concordant left temporoparietal activation in the arithmetic single-file meta-analysis. This suggests that across development, children may not reliably recruit the same temporoparietal regions for arithmetic and phonological processing due to developing fluency with retrieval-based arithmetic. Yet in the adult sample, we see concordant activation in this area for both the single-file arithmetic meta-analysis and the conjunction.

6. Limitations

One important limitation of the present meta-analyses is the heterogeneity in participant ages in the developmental sample, which ranged from 7 to 17 years across arithmetic studies and from about 6 to 14 years across studies involving phonological processing. As a result, areas of common activation in the developmental conjunction analysis likely reflect regions that do not change across developmental time. Therefore, the analysis does not capture, for example, brain regions that support arithmetic during particular points in development. Importantly, this may account for the absence of a temporoparietal cluster for the developmental sample, since recruitment of this regions increases over development (e.g., Ansari, 2008). When additional developmental arithmetic studies are available, future meta-analyses could contrast younger and older children to test this hypothesis.

A second limitation concerns differences in retrieval across arithmetic operations. Retrieval is likely for small addition and multiplication problems but efficiency and use of retrieval may differ by age (Imbo and Vandierendonck, 2008). Further, whether different arithmetic operations recruit different brain regions is still an open question. Several studies have found differentially active brain regions across arithmetic operations (Arsalidou and Taylor, 2011; Chochon et al., 1999; Zhou et al., 2007). However, recent research suggests that neural differences attributed to arithmetic operations per se may be due to surface criteria of problems, and that neural differences may instead reflect differences in strategy use (Tschentscher and Hauk, 2014).

A final limitation concerns the comparison of the arithmetic and phonological contrasts. While we aimed to make the contrasts as similar as possible across domains, many of the developmental phonological processing studies use low-level baselines, such as fixation. While meta-analyses are limited to extant research, they also offer insight into gaps in the literature and provide potential research opportunities. We offer that future neuroimaging studies with developmental samples can also include contrasts with high level control tasks, as a way to better understand the mechanisms that underlie phonological processing.

7. Conclusion

The present study used neuroimaging meta-analysis to investigate whether arithmetic and phonological processing − related but distinct domains − share overlapping areas of brain activity. In the developmental sample, areas of concordant activity were concentrated in frontal regions with an additional cluster in left FFG, regions that may support domain-general and symbol processing, respectively. The adult sample yielded left-lateralized clusters in IPL and IFG, suggesting common regions that support connecting symbols with their verbally-stored referents. Across the two conjunctions, children showed more diffuse and frontal activation compared with adults. Such results highlight the engagement of domain-general attentional processes that support more effortful cognitive processing across domains in children. Investigating brain regions that support both arithmetic and phonological processing in children and adults can inform models of how these two processes are related and how the brain may support processing of higher order symbolic representations, such as arithmetic facts or words. Such work can in turn contribute to a better understanding of the neural correlates of learning throughout development and adulthood.

Conflict of Interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.dcn.2017.05.003.

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