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Neurocognitive mechanisms underlying multiplication and subtraction performance in adults and skill development in children: a scoping review

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Many studies investigating the brain correlates of arithmetic processing have either focused on a single operation (e.g. addition), or have averaged brain activation across different operations, a practice that washes away operation-specific effects. This review focuses on the processing of two fundamental operations (i.e. multiplication and subtraction), summarizes recent neuroimaging evidence on the role of the verbal and quantity mechanisms that underlie adults' performance on these operations, and covers the role of these mechanisms in explaining longitudinal gains in typically developing children. Overall, evidence supports that recruitment of verbal mechanisms is important for explaining single-digit multiplication performance and gains, whereas recruitment of quantity mechanisms is crucial for explaining performance and gains in single-digit subtraction.

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Introduction

Given the importance of being knowledgeable in mathematics in our technologically driven society, research has focused on understanding how children learn math with the ultimate goal of optimizing instruction. Owing to the cumulative nature of math learning, becoming fluent with single-digit arithmetic constitutes a building block for more advanced math content.

Behavioral research has been a rich source of information on how children develop their simple arithmetic skill, but is limited in explaining how this development occurs. For example, studies have incorporated self-reported measures with the objective of understanding which strategies are associated with better performance [52,53]. Controversy has emerged, however, regarding the reliability of these measures, participants' awareness of the strategies used, and possible biases introduced by simply asking participants to report them (e.g. Kirk and Ashcraft [45]; see, however, Wu et al. [95] for evidence on the validity of these measures). More recently, researchers have used functional magnetic resonance imaging (fMRI) to investigate the type of neural processing associated with arithmetic problem-solving. This may provide a more implicit measure informing about the type of strategy used by participants to solve problems, notably by identifying the brain regions showing activation when participants solve different types of arithmetic problems, looking for associations between reliance on certain neural mechanisms and concurrent math performance, and by studying to which extent relying on those mechanisms explains gains over time in typically developing children.

One of the most influential models of numeric processing in the adult brain [22] proposes the existence of three brain systems responsible for numeric processing: a system involved in magnitude representation in parietal cortex [92•], more specifically in the bilateral intraparietal sulcus (i.e. IPS), located in-between the inferior and superior parietal lobules (i.e. IPL/SPL, hereinafter, quantity mechanisms), a system responsible for the representation of numbers in verbal format involving perisylvian regions (i.e. hereinafter, verbal mechanisms), and a system linking numerical processing with spatial processing and attention in posterior superior parietal lobule (PSPL).[1] This model describes a differential involvement of these regions, depending on the demands of the task, with the clearest difference being shown between single-digit multiplication and subtraction.

Several reviews have been published recently focusing more broadly on the brain basis of math learning [39,61,62,94], but the current paper aims to review the recent literature supporting the involvement of verbal versus quantity mechanisms in single-digit multiplication and subtraction skill, respectively, and the role of these mechanisms in explaining successful development of these operations in children. This helps fill a gap in the literature because many studies investigating the brain correlates of arithmetic processing have focused on additions (e.g. [71]), compared additions with subtractions (e.g. [96]), or averaged brain activation across different operations (e.g. [5,36]), a practice that washes away operation-specific effects.

The verbal nature of multiplications and the quantitative nature of subtractions

Multiplication does not engage mental number line-based procedures, but subtraction does

The literature suggests that individuals represent numbers as items spatially ordered along a mental number line, with smaller numbers being located on the left of this line and larger numbers being located on the right side [21]. Consistent with this, studies have suggested that numbers are associated with spatial shifts in attention, with small numbers facilitating the detection of a subsequent target appearing in the left hemifield and larger numbers facilitating the detection of targets appearing in the right hemifield [31]. Evidence has shown that these spatial biases are also present in symbolic arithmetic Knops et al. [101]. In an attempt to better understand the association between simple arithmetic and the horizontal shift in attention, Mathieu et al. [60] asked participants to solve single-digit arithmetic problems in which the first operand and an arithmetic sign (+, -, x) were presented one after the other at the center of the screen, and were followed by the second operand presented either to the right or the left of the screen. They found that participants were faster when the second operand appeared in the right hemifield for addition (i.e. consistent with a rightward shift of attention), whereas they were faster when the second operand was presented in the left hemifield for subtraction (i.e. consistent with a leftward shift of attention). No such spatial bias was observed for multiplication. Another study found that the simple presentation of an arithmetic sign (+, -, x) before the arithmetic problem was presented facilitated subsequent additions and subtractions, but not multiplications [30]. Several spatial attention brain regions, including PSPL, showed activation after the presentation of a '+' sign, as compared with a 'x' sign in Mathieu et al.'s [59] study. These findings suggest that subtractions and multiplications may involve different processes, with the former being more quantity-based and affected by the activation of mental number line-based procedural knowledge, and the latter being associated with direct retrieval of facts from memory and not engaging the mental number line.

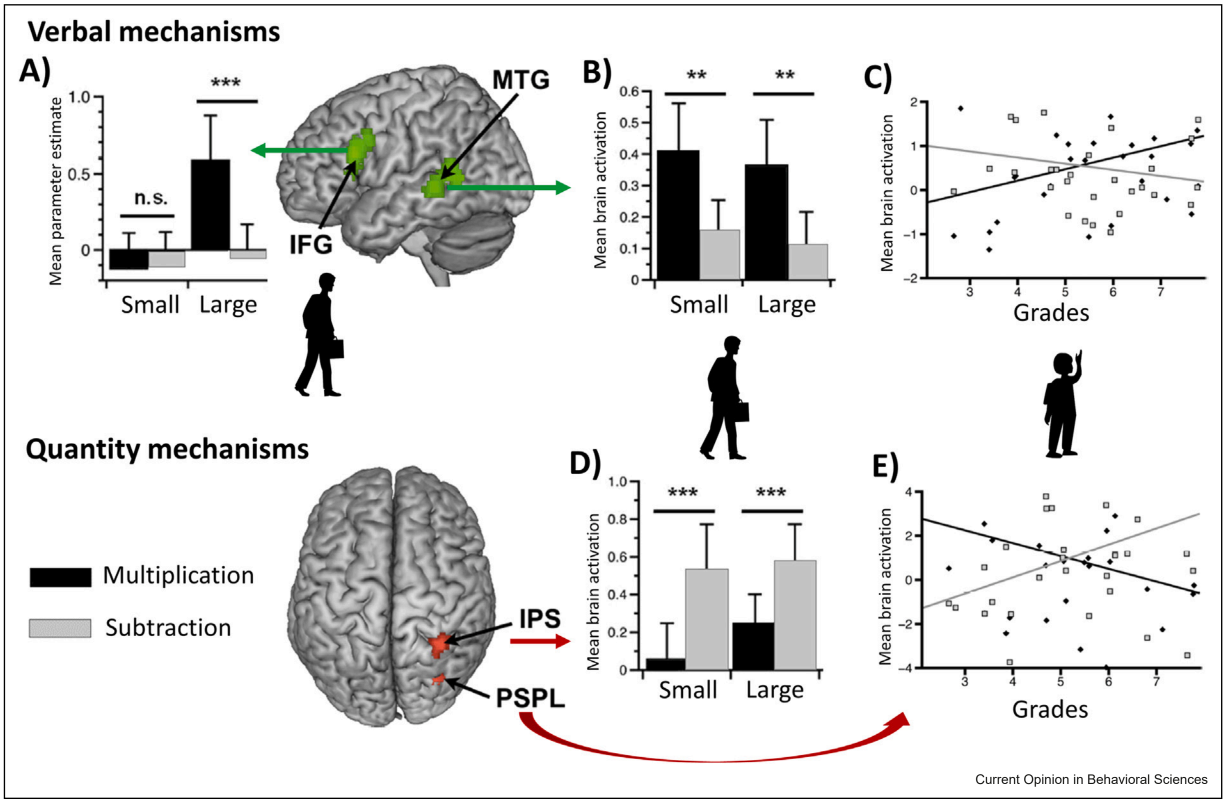
Multiplication and subtraction solving activate different brain regions both in children and in adults

Using fMRI, Prado and colleagues [69] found that solving multiplication and subtraction operations activated different brain regions in adults. They used a dot comparison task to localize quantity mechanisms within the anatomical IPS, a crucial region for quantity processing [22], and a phonological task to identify verbal mechanisms within the left middle and superior temporal gyri (i.e. MTG/STG) considered to be involved in housing the verbal representations in long-term memory and left inferior frontal gyrus (i.e. IFG) thought to be involved in effortful control and retrieval of verbal knowledge from memory [69]. They found that multiplications activated more verbal mechanisms (i.e. left MTG), as compared with subtractions [51] (Figure 1b), and that subtractions activated more quantity mechanisms (i.e. right IPS) as compared with multiplications ([69]; Figure 1d). Larger multiplication problems, specifically, elicited greater left IFG activation than smaller multiplications or subtractions of any size (Figure 1a). Similar parietal activation (IPS, SPL) was reported for single-digit subtraction processing in a study with 7- to 29-year-old participants [29] and in a study comparing two-digit subtractions with a number-matching task in adults [96]. These regions also showed activation for multiplications and subtractions in a meta-analysis with adults [6]. While most of this evidence comes from hearing adults, a recent study has shown that multiplication and subtraction are processed differently not only by hearing adults, but also for Deaf American Sign Language native signers, with both groups recruiting quantity mechanisms to solve subtraction problems [11•], but not multiplications.

Prado et al. [68] extended the findings obtained in adults to 2nd- to 7th-grade children by showing grade-related increases in MTG for multiplication (Figure 1c) and in

[1] In this review, we treat PSPL as part of the quantity-processing system, since it has been found in studies requiring the manipulation of numerical quantities both in adults [6] and in children [44], with evidence suggesting that it may support some of the spatial and attentional processes associated with the procedural manipulation of numbers [22]. Research supporting this comes, for example, from studies with adults showing overlapping patterns of activity in the PSPL for addition and rightward shift of attention and for subtractions and leftward shifts of attention [48], such as the ones needed to remove or add quantities along a mental number line.

Figure 1



Different recruitment of verbal and quantity mechanisms by multiplication and subtraction. Note that small and large problems were combined in Figs. C and E. Note that clusters are shown to illustrate anatomical regions and do not necessarily represent the cluster from which brain activation was extracted. For multiplications, small problems comprised two operands smaller than or equal to 5 (e.g. 3 × 4), whereas for large problems, both operands were larger than 5 (e.g. 6 × 8). For subtractions, small problems had a small difference between the first and second term (regardless of the first term size, e.g. 3–2), whereas large problems had a large first term and a large difference between the first and second terms (e.g. 9–4). **(a)** Bar chart showing greater left IFG activation for large multiplication problems in adults [69]; **(b)** Bar chart showing greater left MTG activation for multiplication problems as compared with subtractions in adults [69]; **(c)** Scatterplot showing increases in left MTG to solve multiplications with more years of math instruction in children [68]; **(d)** Bar chart showing greater activation for subtractions than for multiplications in right IPS in adults [69]; **(e)** Scatterplot showing increases in right PSPL to solve subtractions with more years of math instruction in children [68].
Figure adapted from Prado et al. [68,69].

PSPL for subtraction (Figure 1e) with more years of math instruction, which were more pronounced for smaller problems. They interpreted these findings as showing more robust representations of multiplication facts in memory (i.e. MTG increases) and the acquisition of efficient quantity manipulation procedures relying on attentional shifts for subtraction ([59], i.e. PSPL increases) with more years of math education. They also found grade-related decreases in frontal cortex (i.e. left IFG) for multiplications, suggesting a more automatic and less effortful retrieval of arithmetic facts with more years of math instruction, probably as a result of those representations becoming more robust in memory. Similar decreases in frontal activation were found after multiplication training in a study using functional near-infrared spectroscopy (fNIRS) with adult participants [99], suggesting more efficient retrieval after extensive practice. Figure 1 shows the different engagement of verbal versus quantity mechanisms by multiplications and subtractions, respectively [69], and the grade-related changes in those areas with more years of math instruction [68].

The controversial role of other perysilvian regions in multiplication: the Angular Gyrus

Besides the perysilvian regions (MTG, STG, and IFG) found by Prado and colleagues, Dehaene and colleagues [22] model of numeric processing also postulates that the Angular Gyrus (AG) is involved in representing numbers in verbal format, therefore playing a crucial role in the retrieval of arithmetic facts from long-term memory. AG activation was found, for example, in studies in which adults were intensively trained in solving complex arithmetic problems, particularly when comparing brain activation for trained and untrained (i.e. to be trained) problems in the post-training session (e.g. [23]). Bloechle et al. [12], however, questioned this approach by suggesting that comparing trained problems before and after training would more clearly reflect the process of arithmetic fact learning. Extensively training adults in solving two-digit by one-digit multiplication problems, Bloechle et al. [12] found no AG activation when this comparison was used. Instead, they found activation in bilateral perisylvian regions of the brain. In addition, no increase in connectivity encompassing the AG was found in a study comparing diffusion parameters extracted from fiber tracking before and after a 5-session training of two-digit by one-digit multiplication problems in adults [47]. Moreover, a recent study using transcranial magnetic stimulation while adults solve multiplications (i.e. single-digit) and subtractions (i.e. tens minus single digit, requiring carry) found that direct stimulation of the left AG had a disruptive effect on the retrieval of both multiplications and subtractions, as well as on the calculation of multiplications in adults [32], questioning the supposed role of AG in retrieval.

Lack of evidence of Angular Gyrus involvement in multiplication processing in children

Studies on arithmetic problem-solving with children have, in general, found no AG effect (for exceptions, see Polspoel et al. [66] or Wang et al. [100]). Rosenberg-Lee et al. [73] did not find greater AG activation for single-digit multiplication as compared with single-digit subtraction, challenging the view that AG is involved in fact retrieval. The same group found decreases in AG activation (instead of increases) with increased use of retrieval strategy after a simple addition and subtraction training [74]. In addition, no AG activation was obtained when comparing trained and untrained problems in the post-training session, or when comparing the pre- and post-training session for trained problems in a study training 9-to-10-year-old children in solving simple (single-digit) and more complex (two-digit by single-digit) multiplications [20••].

Using fNIRS to study simple (single-digit) and complex (single-digit by two-digit) multiplications, Soltanlou et al. [79] not only found no increases in left AG activation after multiplication training in children but an unexpected increase in AG for untrained problems (i.e. post-test vs. pre-test). In a longitudinal fNIRS study asking adolescents to solve a written production task including the four operations and different complexity levels, Artemenko et al. [8] found longitudinal changes in parietotemporal activation for multiplication task solving, which went from deactivation in grade 6 to activation in grade 7. However, the parietotemporal region of interest in this study included both AG and MTG, so no conclusion could be reached regarding the unique contribution of each of these regions in explaining brain activation changes.

Alternative functions of the Angular Gyrus and its possible role in arithmetic processing

Some studies have suggested that AG is unrelated to arithmetic processing, but shows task difficulty-related differences [50]. For example, the AG is an important node in the default mode network, and might therefore show stronger deactivation when task difficulty increases [35,42]. This would be consistent with the fact that the default mode network shows stronger deactivations with more difficult tasks [14]. This would also explain why numerous studies on arithmetic processing have found deactivation, not activation, of this region when comparing the math condition with a baseline or control condition (e.g. [42]). A recent study obtained direct intracranial recordings in the AG and surrounding areas in the parietal cortex from epileptic patients while they solved different arithmetic tasks. The results indicated that the majority of activated sites in left AG showed deactivation, not activation, and that no difference emerged when comparing multiplications and additions [63••].

Alternative functions have been suggested for AG, including its role in the automatic mapping between math symbols and their semantic referents [4], or a strategy selection decision process, with this region controlling whether fact-retrieval processes are recruited or not to solve a task [12]. Outside the field of math, a recent study integrating the findings from the episodic and semantic memory literature, proposed a unifying model of AG function according to which this area would enable the online dynamic buffering of multisensory spatiotemporally extended representations [38].

Three recent studies have suggested interesting ideas regarding the role of AG in arithmetic. First, Chang et al. [18] found that only the anterior part of AG showed age-related changes in children, but not the posterior part. This suggests that a more careful look at the subparts of this structure may clarify its precise role in arithmetic learning. Second, a recent study investigating white matter connectivity in acute left- and right-hemisphere stroke patients while they solved multiplications found that the disconnection between AG and temporal areas such as MTG, STG, and superior temporal sulcus was specifically detrimental to fact retrieval [78••]. Future studies should address the role of the connectivity between these regions in explaining multiplication performance and its role in explaining longitudinal gains in children. Third, a study obtaining intracranial recordings of the AG and surrounding areas found that the sites showing activation in AG were actually located at the border zones with IPS [63••]. According to these authors, given that the posterior parietal cortex comprises distinct functional regions that are in close anatomical proximity, it is possible that previous research had located the effects in AG after coarse anatomical group-level analysis that blurs the anatomical boundaries across subjects (i.e. effects were not really in AG, but nearby).

Evidence from hippocampal activation in arithmetic comes mostly from research on addition, not multiplication

Whereas not per se a verbal area, the hippocampus plays a critical role in memory and learning [56,75]. Most of the studies reporting the involvement of this region in arithmetic have used addition tasks, not multiplication (for exceptions see [12] or [47]). Hippocampal activity has been found, for example, in a cross-sectional study investigating 7- to 29-year-old participants, with activity in this region increasing with increasing age during addition, but decreasing during subtraction [29]. Enhanced hippocampal activation was also found by studies showing increased retrieval rates [74], and more efficient memory retrieval [89] after an 8-week training program designed to promote speeded practice of arithmetic in elementary school children. A longitudinal study with 7-to-9-year-old children showed that the transition from quantity-based to retrieval-based strategies paralleled increased hippocampal and decreased prefrontal–parietal engagement during addition task solving. Increased functional connectivity between the hippocampus and neocortical regions predicted gains in retrieval-based strategies [71].

Hippocampus activation, however, is not typically found in multiplication task solving in children. For example, no hippocampus activation was found when comparing brain activation before and after multiplication training or when comparing trained and untrained multiplication problems in the post-training session in children [20••]. Why would multiplication task solving not activate the hippocampus if multiplications, such as additions, are stored and automatically retrieved from memory? Qin et al. [71] suggested that the hippocampus may have a time-limited role in fact retrieval, showing activation only in the early stages of arithmetic fact learning (i.e. children), when arithmetic facts are being encoded in long-term memory, but not later on (i.e. adolescents and adults), after the consolidation of these facts in memory. The lack of hippocampus involvement in adults is supported by a recent study showing that atrophy to this brain region had no impact on the retrieval of over-learned multiplication facts in adults with Alzheimer's disease [24]. It is then possible that studies with addition have found hippocampus activation because they have studied relatively younger children (e.g. 7-to-9 years old, [29,74,89]), while multiplication studies may have missed this effect because they studied relatively older children (e.g. 10-to-11 years old [20••,68]).

The literature has not yet clarified, however, whether brain activity associated with additions is more consistent with the idea that facts stored and automatically retrieved from memory, such as multiplications (i.e. fact-retrieval hypothesis, e.g. [71]) or whether addition problems are solved by quantity-based procedures that become more efficient and automatic with practice (i.e. schema-based hypothesis; for more literature on this debate, see Barrouillet and Thevenot [9]; Fayol and Thevenot [30]; Grabner et al. [34]; Suárez-Pellicioni et al. [82]; Thevenot et al. [90]). Supporting the schema-based hypothesis, Mathieu, Epinat-Duclos, Léone et al. [58] found hippocampal activation when children were merely presented with the addition sign (i.e. '+'). Given that they had previously localized the hippocampus as a region of interest being involved in spatial attention processing, these findings were interpreted as supporting the idea that solving additions recruits quantity-based procedural knowledge based on spatial attentional shifts on the mental number line. The hippocampus, however, did not show activation when a multiplication sign ('x') was presented, which was attributed to the different nature of these two operations, with multiplications not engaging mental number line-based procedural mechanisms and rather being solved by the automatic retrieval of multiplication facts from memory. Contrary to the role of hippocampus in the encoding of addition facts (i.e. fact-retrieval hypothesis, [71]), these researchers suggested that the hippocampus may help build associations between space and certain arithmetic operations (e.g. '+') over development.

Consistent evidence on the quantitative nature of subtraction and its underlying neural architecture

While different brain regions have shown activation for multiplication across studies, less discrepancy exists for subtractions. This could be because the former has been more extensively studied than the latter. The evidence seems to converge in supporting the quantitative nature of subtractions both for adults and for children, and the crucial role of the bilateral IPS, considered to be the primary neural correlate for magnitude representation, in explaining performance. This seems to be the case both for hearing English speakers and deaf signing adults, with both groups recruiting the right IPS to solve single-digit subtractions [3].

Convincing evidence of the quantitative nature of this operation was provided by Prado et al.'s [69] study in adults. In addition to finding greater activation of right IPS by subtraction as compared with multiplication, a multivoxel pattern analysis (MVPA) revealed a significant correlation between the strength of numerical distance effects in the dot comparison task in the IPS and the response to subtraction versus multiplication in this region, suggesting an overlap of activation between subtraction and quantity processing at the neuronal level. Slightly different subregions of the IPS were engaged by subtraction and quantity representation in the Castaldi et al. [16] study comparing brain activation elicited by a symbolic and nonsymbolic comparison task and a two-digit minus single-digit subtraction task in adults. Preferential activation in bilateral IPS was found for single-digit subtraction as compared with single-digit addition in 7- to 29-year-old participants [29]. Age-related increases in the bilateral IPS were found in a study comparing children, adolescents, and adults solving relatively complex subtractions (i.e. first operand ranging from 3 to 14 and second operand between 2 and 5) [18]. Instead of focusing on operation, Polspoel et al. [66] studied brain activation depending on the strategy reported to solve single-digit and mixed (i.e. two-digit by/minus two-digit) multiplication and subtraction problems. They found increased activation in the bilateral inferior and superior parietal lobes, including IPS, in 4th graders during problems reported to be solved by procedures as compared with those reported to be retrieved, regardless of operation.

While these studies found the effects bilaterally, the role of left and right parietal cortex for subtraction task solving is not yet fully understood. A transcranial magnetic stimulation study with adults questioned the role of left IPS in subtraction showing that the left IPS exhibited no involvement in a subtraction task [32]. They found that direct stimulation of the horizontal portion of the left IPS had no detrimental effect on solving subtractions, regardless of the strategy used, which was interpreted as indirect evidence that the right IPS was enough to solve the task. Other studies, on the other hand, have pointed to the involvement of the bilateral IPS in subtraction in both children (e.g. Suarez-Pellicioni et al. [82]) and adults [43•]. Besides the evidence suggesting that right and left IPS show greater activation for nonsymbolic and symbolic tasks, respectively [28•], the factors explaining this lateralization are still under investigation. For example, Artemenko et al. [7] suggested that differences in lateralization of the IPS could be shaped by hand lateralization. They found that left-handed adults had a stronger functional right-lateralization in the IPS than right-handers when solving an approximate calculation task.

In addition to better understanding the unique role of the left and right parietal lobes for arithmetic processing, we need to investigate how these two lobes work with one another to support arithmetic performance. Studies have shown that functional connectivity between left and right IPS positively correlates with arithmetic skill [70], and suggested that connectivity was an important mechanism supporting higher-level numeric problem-solving abilities [10], but no study has yet investigated the role of this connectivity in explaining subtraction performance or subtraction gains over time.

Neural mechanisms explaining longitudinal gains in multiplication and subtraction

Although the number of longitudinal studies in the field of math cognition is small, some evidence has started to show that the successful development of multiplication and subtraction skill depends on a different reliance on verbal versus quantity mechanisms.

The role of verbal mechanisms in predicting multiplication gains

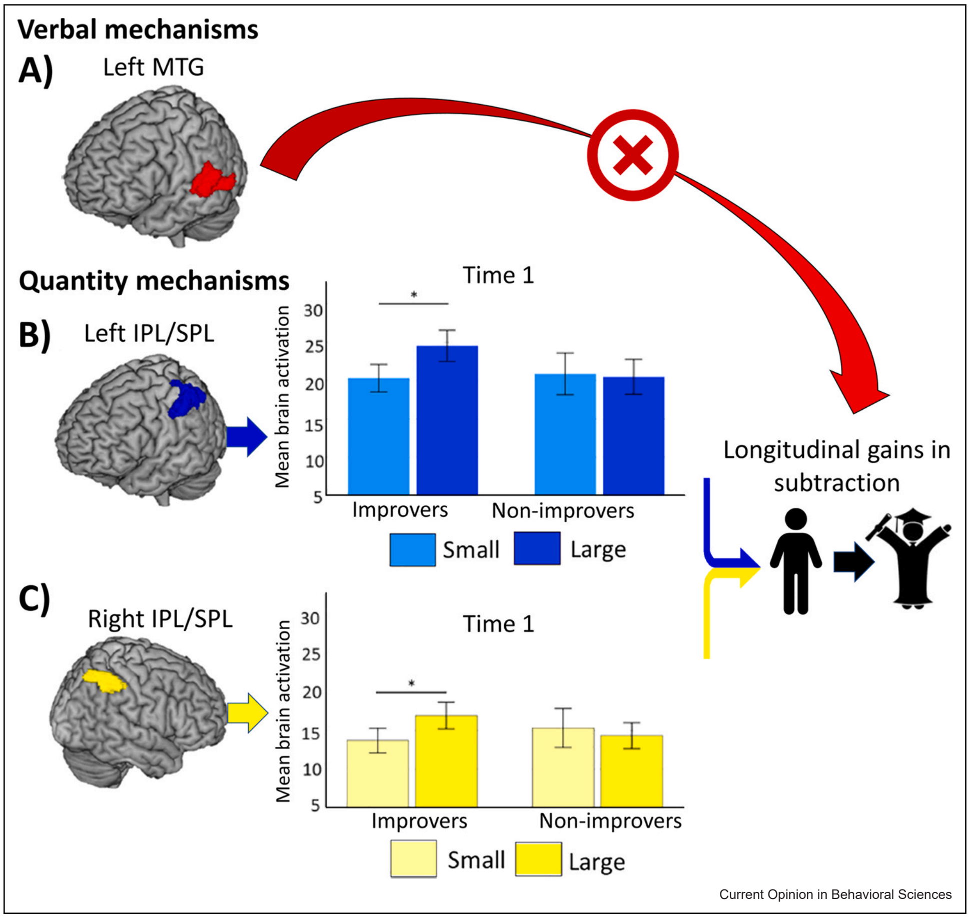
Clear evidence supporting the verbal nature of multiplications was provided by Suárez-Pellicioni et al. [84]. Instead of looking at brain activation during multiplication in brain regions previously localized with a phonological task, this study used brain activation during a phonological task as the predictor of single-digit multiplication gains over time. This study revealed that greater reliance on phonological representations (i.e. greater MTG/STG) and more automatic access to them (i.e. reduced IFG) predicted gains in math tasks that emphasized the rapid retrieval of the solution from long-term memory (i.e. multiplication or math fluency), but not when the task relied more on quantity mechanisms, such as subtraction. This effect was shown only by younger children (i.e. 10 years old), not older ones (i.e. 12 years old), suggesting that phonology may play a more important role in early stages of arithmetic fact learning.

In another study, the role of a structural measure, gray matter volume (GMV), in verbal (i.e. left MTG/STG) and quantity (i.e. bilateral IPS) regions, was investigated in predicting gains in single-digit multiplication and subtraction skills over time in children (Suárez-Pellicioni et al. [83•,86••]). This study found that GMV in left MTG/STG was concurrently associated with higher multiplication skill in children, so the higher the GMV in this region, the better children's multiplication skill. Structural integrity of this region, however, did not predict multiplication gains over time. While the former finding adds to the previous literature showing the verbal nature of multiplication, the latter suggests either a time-limited role of the structural integrity of this region in explaining skill development or a lack of sensitivity of this measure in predicting gains over time. Interestingly, GMV in verbal regions (left MTG/STG) predicted smaller gains in subtraction, which highlights the clear differences between these two operations.

The role of quantity mechanisms in predicting subtraction gains

Suárez-Pellicioni et al. [83•,86••] also examined whether GMV in left IPS predicted gains in subtraction skill for young children (i.e. 10 years old). They found that the higher the GMV in this region, the more gains they showed two years later [83•,86••]. IPS structural integrity, however, played no role in predicting multiplication gains. In another study, Suárez-Pellicioni et al. [82] investigated whether relying on verbal versus quantity areas predicted gains in subtraction fluency over time. Answering this question was important to clarify whether fluency in this operation is achieved

Figure 2



Role of verbal and quantity mechanisms in temporal and parietal cortices, respectively, in explaining longitudinal gains in single-digit subtraction fluency. **(a)** Illustration showing no effect of brain activation in left MTG in predicting longitudinal gains in subtraction fluency. Bar chart showing a greater neural problem-size effect (i.e. large vs. small) in the left IPL/SPL **(b)** and in the right IPL/SPL **(c)** for improvers in subtraction fluency, but no effect for nonimprovers. For subtractions, small problems had a small difference between the first and second term (regardless of the first term size, e.g. 3–2), whereas large problems had a large first term and a large difference between the first and second terms (e.g. 9–4).
Figure adapted from Suárez-Pellicioni et al. [82].

by retrieving solutions from memory (i.e. fact-retrieval hypothesis) or by quantity-based procedures becoming more efficient with practice (i.e. schema-based hypothesis). As shown in Figure 2, this study revealed that improvers showed a larger neural problem-size effect[2] in the bilateral parietal cortex at T1, whereas no effect was found in verbal regions [82]. Brain activation in parietal cortex showed reductions over time, and was accompanied by a reduction in frontal regions over time (bilateral MFG/right IFG), suggesting that quantity-based procedures became more efficient, a crucial claim of the schema-based hypothesis. A recent study using fNIRS also found reductions in parietal and frontal cortices after a multiple-day two-digit subtraction training in adults, which was interpreted, indicating that training improved the efficiency of subtraction calculation [99].

Recruitment of quantity mechanisms by multiplication is associated with smaller gains

Although activating quantity mechanisms was associated with gains in subtraction (Suárez-Pellicioni et al. [82]) and structural integrity of this region predicted subtraction gains (Suárez-Pellicioni et al. [83•,86••]), relying on this region to solve multiplications was associated with a lack of longitudinal gains [85]. Studying functional

[2] The problem-size effect is a robust finding in numerical cognition referring to the fact that response times and error rates increase as the magnitude of the operands in an arithmetic problem increases [81]. For example, a participant will make more errors and will be slower in answering larger problems such as '9 + 7' as compared with smaller problems such as '3 + 2'. The neural problem-size effect refers to differences in brain activation for problems of different size (i.e. greater for larger problems), which has been reported both for adults [80] and for children [19].

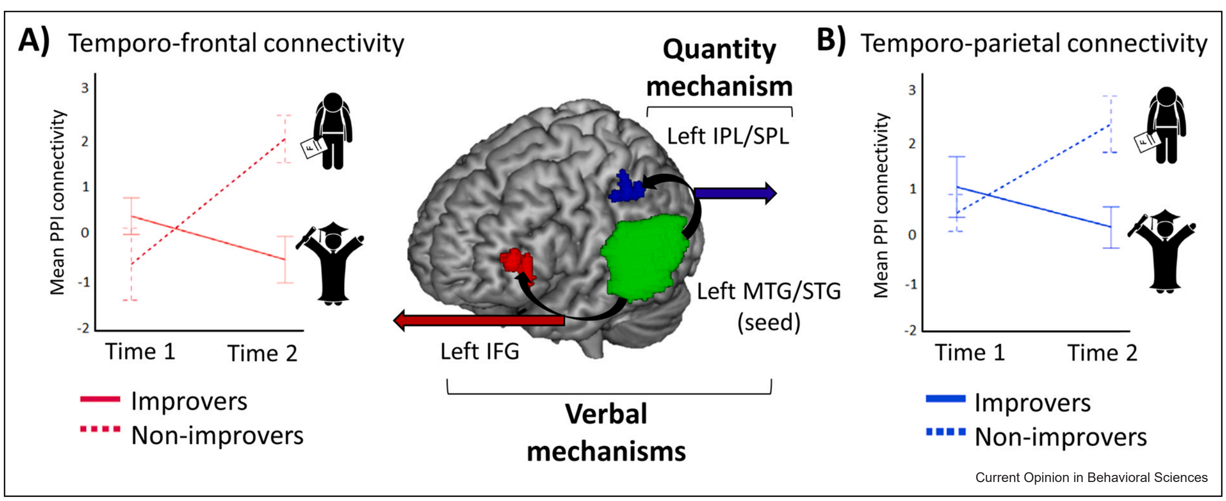
connectivity (i.e. psychophysiological interaction), we found that lack of multiplication fluency gains in larger problems was associated with an increase in functional connectivity between verbal and quantity regions (i.e. left MTG/STG and IPS) and within language regions (i.e. left MTG/STG and IFG). This finding was interpreted as the lack of fluency gains being associated with reverting to parietal-based backup strategies (Figure 3b) after two years, a strategy that may have higher demands on working memory (i.e. enhanced IFG, Figure 3a) [85]. Participants showing this reversion not only showed a lack of gains in the task solved while being scanned but also on a standardized test of multiplication skill solved outside the scanner. Additional evidence for less involvement of quantity mechanisms in the parietal cortex being associated with successful multiplication learning is an fNIRS study in adults that found that weaker resting-state functional connectivity between parietal and frontal cortices before the training was related to better learning of two-digit by one-digit multiplications [99]. Greater involvement of quantity mechanisms in multiplication task solving may be more beneficial in those with altered access to verbal representations. For example, deaf signing adults activated the right IPS to solve single-digit multiplications, suggesting that they were engaging more in calculation to solve these problems, whereas hearing English speakers were not [3].

Beyond cognition: the neural bases explaining the role of environmental and attitudinal factors

Mathematical ability is determined by the interplay between genetic and environmental factors [72]. While some studies have started to unravel the neurocognitive mechanisms explaining the effects of genetics on math ability in children [77], very little is known about the brain correlates explaining the effect of environmental and attitudinal factors on math performance. The different numeracy experiences that children have at home, for example, play an important role in explaining math performance. A recent study found that differences in the frequency of numeracy practices shared with parents explained left IPS activation to the repeated presentation of Arabic numerals in 8-year-old children [33••].

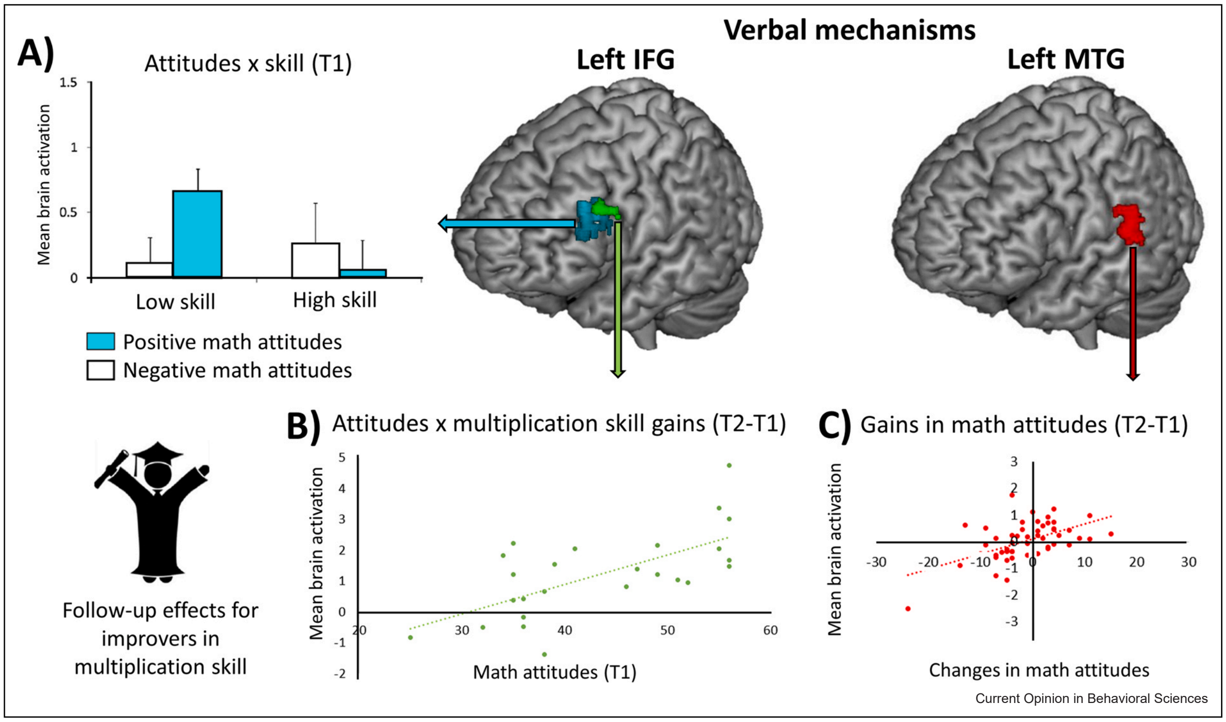
Another important environmental factor affecting performance is the family's socioeconomic status (SES). A study found that SES impacted the recruitment of IPS during single-digit subtraction task solving, with children from higher SES decreasing right IPS activation and increasing left MTG activation with increasing levels of math fluency, suggesting they relied more on retrieval and less on quantit- based mechanisms [25]. A recent review reported that 17 out of 18 studies found an association between SES and family math engagement

Figure 3



Association between changes in functional connectivity between verbal and quantity areas over time and multiplication fluency gains. **(a)** Line graph showing increases in functional connectivity between left temporal (i.e. left MTG/STG, seed) and frontal cortices (i.e. left IFG) for children showing a lack of fluency gains in multiplication, suggesting increases in the reliance on cognitive control for this group. **(b)** Line graph showing increases in functional connectivity between left temporal (i.e. MTG/STG, seed) and parietal cortices (i.e. left IPL/SPL) for children showing a lack of fluency gains in multiplication, suggesting increases in the reliance on quantity-based backup strategies for this group.
Figure adapted from Suárez-Pellicioni et al. [85].

Figure 4



The association between verbal areas in frontal and temporal cortices and math attitudes. **(a)** Bar chart showing the interaction between math skill and math attitudes at T1, extracted from the cluster in cyan in left IFG [26]. **(b)** Scatterplot showing increases in left IFG activation as math attitudes become more positive, only for children showing longitudinal gains in multiplication skill, as extracted from the cluster shown in green (Suárez-Pellicioni et al. [83•,86••]). **(c)** Scatterplot showing that greater left MTG activation at T1 is associated with math attitudes becoming more positive over time, as extracted from the cluster in red (Suárez-Pellicioni & Booth [87•]).
Figure adapted from Demir-Lira et al. [26], Suárez-Pellicioni et al. [83•,86••], and Suárez-Pellicioni & Booth [87•].

[27]. SES and family math engagement not only showed a positive association [54], but there were qualitative differences in engagement based on the family's SES. Lower-SES families, for example, engaged in less math-focused number talk or academic content during pretend play as compared with middle-class families [93]. Children from higher SES families may have encountered more opportunities to practice subtractions at home, leading to a better representation of these problems and their solutions in long-term memory, and therefore more reliance on retrieval [25].

The brain correlates associated with the interaction between math ability and attitudinal factors have rarely been addressed. To this aim, Demir-Lira et al. [26] investigated the brain correlates explaining the interaction between math attitudes and math skill when children solved single-digit multiplication problems while being scanned. As shown in Figure 4a, we identified a cluster in left IFG showing greater activation for lower-skill children having positive math attitudes. Those with positive attitudes may invest more effort in solving the multiplication task as compared with their peers with negative attitudes. In a follow-up study, Suárez-Pellicioni et al. [83•,86••] examined the interaction between math attitudes at T1 and longitudinal gains in multiplication skill. As shown in Figure 4b, we found a cluster overlapping the one found by Demir-Lira et al. [26] in left IFG, suggesting that effort investment could be the neurocognitive mechanism explaining the positive role of math attitudes in predicting math gains. A recent study from our group also explored whether the neurocognitive mechanisms during single-digit multiplication task solving predicted positive changes in math attitudes over time [87•]. As shown in Figure 4c, we found that activating left temporal cortex at T1 explained longitudinal gains in math attitudes. Given that this analysis also included quantity areas in parietal cortex as Regions of Interes (ROIs), we speculate that this study suggests that training children to retrieve multiplication facts from memory, a more efficient strategy for this operation, might be a way to help them develop positive math attitudes, perhaps by avoiding the errors and frustration associated with the convoluted and demanding nature of calculation-based backup strategies for this operation.

Several other affective factors besides attitudinal ones, such as math anxiety, have effects on math performance and development. Although a review of this literature is outside the scope of this paper, studies have started to unravel the neurocognitive mechanisms explaining its effects in adults (e.g. [64]), the neural basis of its development in children (e.g. [97]), and the effect of possible remediation methods (e.g. [88]).

Discussion and conclusions

Being skilled in math is crucial for securing good job opportunities in today's highly technological world. Becoming fluent in arithmetic as a child is key to the development of more complex mathematical skills. fMRI has provided unique insights into the neurocognitive mechanisms responsible for arithmetic performance [57]. A better understanding of these mechanisms is important, for example, for the definition of 'neuromarkers' that would help us identify children that may later develop difficulties with math learning, even before the start of formal math instruction [49]. This paper aimed at reviewing the recent literature investigating the neurocognitive mechanisms explaining math performance in multiplication and subtraction, and their role in predicting longitudinal gains in these operations.

Several studies have shown how multiplication and subtraction tap differently into verbal and quantity mechanisms. For example, the structural integrity of verbal areas in children was associated with higher performance in multiplications, but it was associated with lower subtraction gains over time [83•,86••]. On the other hand, the recruitment of quantity areas in children, crucial for subtraction performance, was shown to be associated with a lack of gains in multiplication fluency over time [85]. The recruitment of different brain mechanisms by these operations is often attributed to the different strategies children rely on to solve these operations [15], with multiplication being learned by rote and therefore recruiting more verbal processing regions, and subtraction being learned mainly using calculation, therefore relying on quantity-processing areas of the brain.

While our review focused on operation-related effects in the brain, some studies have suggested that some neural effects may not be operation-related but strategy-related. Polspoel and colleagues [66] asked 4th graders to report the strategy they had used to solve subtraction and multiplication problems of different complexity and analyzed brain activation to problems reported to have been solved by procedures and those reported to have been retrieved. Their experiment notably included single-digit multiplication and subtractions, and more complex problems, including single-digit (3–6) by two-digit (12–16) multiplications, and two-digit (21–28 or 31–38) minus single-digit (4–9) subtractions. Therefore, the level of complexity *within* each operation was manipulated. The results show that procedural strategies engaged the IPS, whereas retrieval activated AG, supramarginal gyrus, and MTG, regardless of operation. These results are in keeping with the idea that the likelihood of using quantity-based procedures increases as problems become more complex, both for subtraction and for multiplication. The effects reported in this study as strategy-related might then be to some extent complexity-related.

The effects of problem complexity were also shown in studies using single-digit operations. For example, adults showed greater left IFG activation only for large multiplication problems [69], grade-related increases in left MTG were more pronounced for small than for large multiplication problems [68], and the temporoparietal and temporofrontal connectivity patterns for less fluent children were observed only for large multiplication problems (Suarez-Pellicioni et al. [85]), the ones for which a combination of retrieval and quantity procedures (i.e. derived facts) have mostly been reported [52,53]. This supports the idea that a wide range of strategies is used to solve even single-digit arithmetic problems.

Another factor that could contribute to explaining the reliance on different brain mechanisms for arithmetic problem-solving is participants' age or level of expertise. Older or more skilled children are expected to have a more consolidated and robust storage of arithmetic facts in memory, and therefore to rely more on retrieval as compared with younger or less skilled children, who should rely more on quantity-based procedures. Prado and colleagues [68] showed this age-related effect, with children showing greater activation of the left MTG as they received more years of math instruction. Suarez-Pellicioni et al. [85] showed this skill effect, with only less fluent children showing greater temporoparietal connectivity, suggesting that they engaged in quantity-based backup strategies to solve large multiplications. The role of these verbal and quantity mechanisms appears to change over development. Temporal and frontal cortices identified with a phonological task played a role in explaining multiplication gains only in young children (Suárez-Pellicioni et al. [84]) and higher levels of GMV in left IPS predicted subtraction gains only in younger children (Suárez-Pellicioni et al. [83,86]). Studying relatively narrow age ranges is therefore important to understand the effects of age and expertise on arithmetic processing.

The educational system in which participants learned arithmetic may also be a factor in the differential reliance on brain systems to solve math. Cultural differences have been shown in arithmetic learning. For example, the Chinese education system uses rhyming to teach multiplications and involves extensive rote verbal memorization [98]. In North America, more emphasis is placed on conceptual understanding, and children are not expected to drill multiplication facts as much as in many Asian countries [41]. Indeed, Asian countries expect children to solve arithmetic problems quickly, while in North America, more emphasis is placed on the exploration of different strategies and less on speed [40]. This exploratory approach has been suggested to result in more variability in strategy use in North America than in Asian countries [15]. These cultural effects have been shown in other countries as well. For example, Belgian adults are faster than Canadians in solving arithmetic problems, but slower than Chinese adults [40]. Chinese adults also outperform Germans [55]. It is possible that the greater reliance on verbal versus quantity mechanisms in Prado and colleagues' studies may reflect cross-cultural differences in how these operations are taught. Prado et al. [67] investigated the neural correlates of a single-digit multiplication task in adults educated in China and the United States. They found greater activation for the neural problem-size effect in Chinese as compared with American participants in verbal areas (i.e. left STG) and a greater neural problem-size effect in American as compared with Chinese participants in quantity areas (i.e. right IPS). Chinese adults may put more emphasis on retrieving multiplication facts from memory, whereas their American counterparts tended to use more quantity-based procedures, which might be due to the former group's higher level of mastery of multiplication tables. These cultural differences may have a smaller effect on subtraction. Indeed, a study with Chinese adults reported that two-digit subtraction, as compared with addition, engaged more quantity areas in bilateral parietal cortex [96], particularly the right IPS, areas that have consistently been found in Western children and adults.

Another factor that may explain the recruitment of different brain systems by multiplication is the requirements of the task itself. For example, while studies reporting hippocampus activation have mostly used addition tasks inside the scanner, other studies using multiplications with adults have also found activation in this region [12,47]. This may be due to the fact that these were training studies in which adults were required to *learn new* and relatively complex multiplication problems after extensive repetition. It is possible that this requirement of learning new information is what explains the involvement of the hippocampus, which is believed to play a role in the early stages of arithmetic fact learning, when these facts are being encoded in memory. Other studies may have not found hippocampus activation because the tasks required participants to verify single-digit multiplication facts that were overlearned both in adults and in children. For example, no hippocampus activation was found for multiplications in Rosenberg-Lee et al.'s [73] study with adults, probably because they used single-digit problems that did not require encoding, but the retrieval of already-stored multiplication facts.[3]

As for multiplications, the current view is that multiplication facts are stored and retrieved in a verbal code. For example, the problem-size effect in multiplication is explained by larger, less practiced problems showing weaker and less distinctive memory traces than more frequently encountered small problems [91]. While meta-analyses have previously studied the brain correlates supporting phonology and arithmetic in the brain [65], specific evidence for multiplication is scarce. Using MVPA in adults, one study revealed that the neural mechanisms in left MTG that showed more activation for single-digit multiplication (vs. subtraction) were different than those involved in phonological processing [69]. Moreover, no overlap was found using conjunction analysis to determine whether multiplication and a lexico-semantic processing task activated similar brain mechanisms [37]. These findings suggest that the neural mechanisms supporting language and arithmetic fact retrieval may be different. This is consistent with studies in adults showing independent networks in the brain for processing math and nonmath semantics in mathematicians' brains [1,2]. While arithmetic might become independent of language after a certain level of math skill is achieved, future studies should determine if that is also the case for younger children and how the different subcomponents of language support the development of different operations. Whereas some studies have started to explore this question [13•,17], more research needs to be carried out to clarify how bilingual brains store and retrieve multiplication facts in different languages and the neural basis explaining longitudinal gains in this operation for this population.

It is important to mention that this review has reviewed the evidence on the brain systems children and adults rely on *to a larger extent* to solve single-digit

[3] Prado et al. [69] showed adults activated perysilvian regions in temporal (left MTG/STG) and frontal (left IFG) cortices when solving single-digit multiplications, but these regions showed no activation in Rosenberg-Lee et al.'s [73] study with the same operation, same problem size (single-digit), and same population (adults). Although it is hard to know the reasons for this discrepancy, the condition used as a control in each of these studies may have played a role. While the control condition in Prado et al. [69] was a blue square that turned into red, the control condition in Rosenberg-Lee's study was a number-identification task. Besides the requirements of the task, the nature or requirements of the control condition used for comparison in the fMRI analysis may also contribute to explaining the discrepancies in the literature.

multiplications and subtractions. This does not mean that multiplications and subtractions are uniformly solved by using retrieval and quantity procedures, respectively. Instead, there is substantial intraindividual variability in strategy use and individuals choose what they consider to be a good strategy among a wide range of options that are accessible to them, depending on a variety of factors, such as problem characteristics, participants' age, or level of expertise. Over development, strategy use does not change abruptly but may rather show a series of overlapping waves, with more sophisticated strategies being incorporated, but without completely leaving simpler strategies behind. Simpler strategies remain available even into adulthood, to be used, depending on the context [76].

While this review treated quantity and verbal mechanisms as two distinct systems, recent evidence has also suggested that there may be a continuum between the two, with both systems being concomitantly activated. Using fiber tracking to understand structural connectivity, Klein et al. [46] found that the magnitude processing and fact-retrieval networks, despite being anatomically distinct, showed largely identical activation peaks and fiber pathways across two numerical tasks. This suggests that it may not entirely be a question of which of the two systems is activated, but rather that the two systems are activated concomitantly, working as a functionally integrated circuitry for math processing. Although some studies have revealed the collaboration between these two systems for certain groups of children (less fluent, Suárez-Pellicioni et al. [85]), future studies should continue to investigate the role of the interaction between these two systems in explaining performance and math gains.

CRediT authorship contribution statement

MSP: Writing – original draft, Writing – review & editing; **JP:** Writing – review & editing; **JB**: Writing – review & editing.

Conflict of interest statement

The authors declare that they have no conflict of interest.

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This longitudinal study aimed to investigate the role of left IFG in predicting longitudinal gains in multiplication skill over time in children as a function of math attitudes. A cluster-wise analysis revealed a cluster in left IFG showing a significant interaction between math attitudes at time 1 and longitudinal improvement in multiplication, which was due to improvers with positive math attitudes showing enhanced activation in this region. This suggests that IFG activation, possibly reflecting effort invested in retrieving multiplication facts, is one of the possible neurocognitive mechanisms by which children with positive math attitudes improve in multiplication skill.

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This longitudinal study investigated the role of recruiting verbal mechanisms in frontal (i.e. IFG) and temporal cortices (i.e. left MTG/STG) and quantity mechanisms in parietal cortex (i.e. bilateral IPL/SPL), associated with retrieval and the use of quantity-based backup strategies, respectively, in predicting gains in math attitudes over time while children solved a multiplication task inside the scanner. Results revealed clusters in the left middle to superior temporal gyri at time 1 associated with math attitudes at time 1 and with math attitudes gains over time (Time 2-Time 1). This finding suggests that relying on the storage of arithmetic facts, engaged during memory retrieval, to solve single-digit multiplications is associated with the development of more positive math attitudes over time in children.

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