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A partially shared magnitude system: Common and specialized neural substrates underlying spatial, numerical, and temporal arithmetic

Liangzhi Jia [a], Zhiwei Zhang [a], Chengtao Wang [a], Yuanyi Liu [a], Fangwen Yu [a], Di Zhang [a], Yun Pan [a,b,*]

[a] School of Psychology, Guizhou Normal University, Guiyang, China
[b] Guizhou Educational University, Guiyang, China

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ABSTRACT

Magnitude, such as time, space and number, constitutes a foundational construction of perceptual and cognitive experience. A Theory of Magnitude proposes that these dimensions are processed by a shared magnitude system. However, it remains unclear how this system supports the manipulation of multiple continuous magnitude information, such as arithmetic operation across domains and whether it operates as a fully shared or partially specialized subsystem. Using functional magnetic resonance imaging, we investigated magnitude arithmetic in numerical, spatial and temporal domains. Conjunction analyses were conducted at each arithmetic stage (first operand, second operand, and probe) to identify overlapping activations across magnitude dimensions. To explore domain-specific differences, voxel-wise factorial ANOVA and task-dependent functional connectivity analyses were applied. Conjunction analyses revealed several overlapping neural substrates at each stage, including key components of the magnitude system. Voxel-wise factorial ANOVA demonstrated that numerical and spatial arithmetic showed greater activation in the bilateral superior occipital gyrus and left middle occipital gyrus, whereas temporal arithmetic elicited stronger activation in left precentral gyrus. Functional connectivity analyses revealed that temporal arithmetic showed greater coupling with bilateral precentral gyrus and cerebellum, whereas numerical and spatial arithmetic elicited stronger coupling with left inferior occipital gyrus, by using bilateral IPS as seed regions. In summary, arithmetic across different magnitude domains relies on a shared magnitude network, with numerical and spatial operations depending on visuospatial mechanisms while temporal operations depend on sensorimotor mechanisms. This dissociation indicates that static and dynamic magnitudes are supported by distinct subsystems, providing evidence for a partially shared magnitude system.

1. Introduction

Time, space, and number are fundamental dimensions of human experience that provide a framework for organizing events, objects, and sensations (Dehaene and Brannon, 2010; Gori et al., 2023). From a philosophical perspective, these magnitude dimensions are considered fundamental, a priori categories of knowledge that support broader cognitive and experiential processes (Raysmith, 2022; Togoli et al., 2021). From an evolutionary perspective, the capacity to encode and integrate information about magnitude conferred adaptive advantages and was essential for survival, cooperation, and social cohesion in complex contexts (Pantsar, 2019; Vallortigara, 2018). For instance, early Homo sapiens used temporal estimation to anticipate seasonal cycles, spatial cognition to navigate vast environments, and number discrimination to assess group size and resource availability—cognitive abilities essential for survival, cooperation, and social cohesion in complex contexts (Bacon et al., 2023). Taken together, these perspectives position time, space, and number as core constructs that shape cognitive and behavioral processes. Consequently, elucidating how the brain encodes and integrates magnitude information is essential for uncovering the neurobiological mechanisms that underlie perception and cognition.

Walsh (2003) proposed "A Theory of Magnitude" (ATOM), positing that temporal, spatial, and numerical information are encoded within a unified supra–modal magnitude system, in which magnitude information is mapped onto a shared scalar continuum to facilitate cross–dimensional comparison and interaction (Kido et al., 2025). Neuroimaging studies have revealed overlapping activations across

* Corresponding author at: School of Psychology, Guizhou Normal University, Guiyang, China.
E-mail address: panyun129@163.com (Y. Pan).

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different magnitude domains (Cona et al., 2021, 2024; Hawes et al., 2019; Hayashi et al., 2018). For instance, Skagerlund et al. (2016) employed a single fMRI paradigm to directly compare numerical, spatial, and temporal tasks and, using conjunction analysis, identified overlapping activations in the intraparietal sulcus (IPS), supplementary motor area (SMA), insula, and inferior frontal gyrus (IFG), which proposed constitute a distributed magnitude network. A recent meta–analysis by Cona et al. (2024) corroborated these findings, identifying a "core magnitude network" comprising bilateral IPS adjacent the inferior parietal lobule (IPL), SMA, insula, and IFG that is conjointly activated across spatial, temporal, and numerical tasks. In this network, the IPS is proposed as a hub for abstract magnitude coding and cross–domain integration; the SMA supports sequencing of magnitude–related actions, the insula detects salient shifts and orchestrates network transitions, and the IFG supports top–down control (e.g., working memory and decision–making) (Cona et al., 2024; Skagerlund et al., 2016). Together, these studies support that temporal, spatial, and numerical processing share a generalized magnitude system and rely on common neural substrates.

Previous studies of single–magnitude processing reveal shared behavioral metrics across domains. Crollen et al. (2013), for example, used perception and production tasks in numerical, spatial, and temporal domains and found consistent underestimation in perception, overestimation in production, and significant distance effects throughout. Moreover, research on the SNARC, TiNARC, and STEARC effects points to a similar spatial mapping across numerical, spatial, and temporal judgments, with faster left–hand responses for smaller magnitudes and faster right–hand responses for larger magnitudes (Mariconda et al., 2022; Scozia et al., 2024; Zhang et al., 2025). Nevertheless, accumulating evidence suggests that such spatial coding of time and number is largely task–dependent rather than inherent. For instance, robust SNARC effects are typically observed when tasks explicitly bind magnitude(small/larger) codes to spatial(left/right) codes within a unified response mapping (Pinto et al., 2021), and reliable space–time congruency emerges only when the task concurrently engages temporal (past/future) and spatial codes (Scozia et al., 2023a, 2023b). However, most research has focused on single–magnitude processing, leaving it unclear whether these shared mechanisms extend to continuous, multi–step operations such as mental arithmetic, which involves the transformation and comparison of multiple magnitudes and likely engages attentional and working memory systems (Dehaene et al., 1999; Dehaene and Brannon, 2010; Hartmann and Dumureau, 2025). McCrink et al. (2007) proposed the attentional–shift account, in which numerical addition and subtraction unfold by encoding the first operand on the mental number line (MNL), shifting attention by the second operand's magnitude, and translating the resulting position into a response code (Bonato et al., 2021; Prado and Knops, 2024). Behavioral studies found that numerical addition and subtraction arithmetic induce right and left spatial–attention shifts, suggesting that numerical arithmetic inherently relies on dynamic reallocations of spatial attention along the MNL (Haman and Lipowska, 2021). Neuroimaging studies have further demonstrated that congruent spatial cues enhance activation of the posterior parietal cortex (PPC) involved in spatial attention during numerical arithmetic (Knops et al., 2009). According to ATOM, time, space, and number are linked by a common metric for action (Crollen et al., 2013; Walsh, 2003), it is plausible that similar attentional-shift mechanisms may also contribute to spatial and temporal arithmetic; however, direct evidence for this prediction remains limited.

Moreover, previous research has generally regarded the shared magnitude system of time, space, and number as fully integrated, suggesting that all magnitude dimensions share the same spatial encoding, a form of evolutionary exaptation that gives rise to rich cross–domain correspondences (Crollen et al., 2013; Dehaene and Brannon, 2010; Vicario et al., 2013). However, some findings challenge this view (Cappelletti et al., 2014; Cona et al., 2021, 2024; Shukla and Bapi, 2021; Üstün et al., 2022). Studies of developmental dyscalculia (DD) indicate a potential developmental trajectory: children with DD often show impairments across multiple magnitude domains (Skagerlund and Träff, 2014), whereas adults with DD tend to exhibit selective numerical deficits but relatively preserved spatial and temporal abilities (Cappelletti et al., 2014). This pattern suggests that magnitude processing may be more integrated early in development and become increasingly domain–specific with maturation. Cona et al. (2021) further demonstrated topographic gradients within the IPS, SMA, and IFG, with subregions tuned to specific magnitude dimensions. Based on these findings, Üstün et al. (2022) proposed that the magnitude system is only partially shared, with a core network centered on the posterior parietal cortex (PPC) supporting basic magnitude representation and interaction, while each dimension depends on specialized neural substrates. Therefore, it remains to be determined whether the magnitude system is fully integrated or only partially shared, and if the latter, which neural substrates subserve each magnitude dimension.

In summary, although magnitude processing in time, space, and number shows overlapping behavioral effects and neural engagement, it remains unclear whether arithmetic draws on shared operational mechanisms across these domains or instead relies on partially distinct, domain–specific networks, given that arithmetic requires the structured manipulation of multiple magnitudes. Evidence for a shared magnitude system comes from overlapping activations for time, space, and number in core magnitude–related brain regions (Cona et al., 2024; Skagerlund et al., 2016). Distinct arithmetic operations, however, recruit specialized neural circuits (Dehaene et al., 1999; Okuyama et al., 2024) and exhibit different patterns of functional connectivity (Park et al., 2013). Therefore, we used a functional magnetic resonance imaging (fMRI) paradigm with arithmetic tasks in three domains—numerical (non–symbolic number), spatial (line length), and temporal (duration)—and performed conjunction analyses to identify overlapping activations across processing stages (first operand, second operand, probe stimulus). We then conducted a 3 × 3 repeated–measures ANOVA (magnitude dimension: number, space, time × arithmetic stage: first operand, second operand, probe stimulus) on whole–brain voxel–wise data, alongside functional connectivity analyses, to determine whether distinct cognitive processes underpin arithmetic in each domain.

In line with previous research (Cona et al., 2021; Skagerlund et al., 2016; Walsh, 2003), we hypothesize that time, space, and number will show overlapping activation in the core regions of the magnitude system at each arithmetic stage. Furthermore, although substantial evidence supports a shared operational network for number and spatial processing (Hawes et al., 2019; Vallortigara, 2018), it remains debated whether temporal processing engages the same mechanism (Shukla and Bapi, 2021). Neuroimaging studies suggest that temporal processing is served by a distributed network whose engagement depends on the timescale (Mauk and Buonomano, 2004; Paton and Buonomano, 2018). Millisecond intervals timing primarily involves the cerebellum and sensorimotor circuits, whereas suprasecond intervals timing recruit parietal and cortico–striatal systems more heavily (Boven and Cerminara, 2023; Mondok and Wiener, 2023). In contrast, numerical and spatial arithmetic consistently engage the visuospatial circuits (Hubbard et al., 2005). We hypothesize that temporal arithmetic relies on partially distinct processing mechanisms and will engage sensorimotor circuits and the cerebellum more strongly than numerical and spatial arithmetic.

2. Materials and methods

2.1. Participants

A priori power analysis was performed using G*Power 3.1 (Faul et al., 2007). Based on a repeated–measures ANOVA design (as used in Belfi et al., 2019) with an alpha of 0.05, power of 0.80, and a medium effect size ($\eta^2 = 0.08$), the analysis indicated a required sample size of 20. To ensure greater robustness, 30 right–handed undergraduate students (15 males; age range 19–26 years, $M = 23.03$, SD = 1.47) were

recruited via an online participant platform and campus posters. All participants were native Mandarin speakers with normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. Participants provided written informed consent prior to participation and received monetary compensation.

2.2. Materials and procedures

We employed a within–subjects experimental paradigm featuring three magnitude arithmetic tasks: numerical (using non–symbolic quantities), spatial (line–length estimations), and temporal (involving duration judgments). Each task was administered across two separate runs, with the order of tasks systematically counterbalanced among participants to minimize potential order effects.

The numerical arithmetic task followed Jang and Hyde's (2020) paradigm. On each trial, participants viewed two sequential dot arrays (500 ms each; 500 ms interstimulus interval (ITI)) and then judged whether a centrally presented probe array corresponded to the correct sum or difference of the preceding arrays. To control non–numerical visual cues, half of the trials were area–congruent (total dot area proportional to number), and half were incongruent (dot area held constant while number varied) (Jang and Hyde, 2020; McCrink et al., 2007).

The spatial task was a modified version of the paradigm used by Skagerlund et al. (2016). While the original task involved comparing two consecutively displayed lines to determine which was longer, our study adapted this design by requiring participants to assess whether a centrally presented probe line represented the correct or incorrect sum of the lengths of two previously shown lines. These lines, which varied in length from 40 × 30 pixels to 480 × 30 pixels, were presented sequentially at the center of the screen for 500 ms each, with a 500 ms ITI.

The temporal task was modified from Bonato et al. (2021), in which participants were asked to reproduce the duration corresponding to the sum or difference of two auditory time durations by pressing a key for the resulting time. To minimize potential biases introduced by different sensory modalities, all stimuli were presented with the same visual appearance as in the numerical and spatial tasks; only the duration varied (200–2400 ms for each stimulus, with a fixed 500 ms ITI).

Each task was presented in two fMRI runs of 32 trials each (64 trials per task). Trial order was randomized within runs. We recorded accuracy and response time (RT) on each trial. Stimuli were presented using Meide fMRI Audiovisual Stimulation System and responses were made on a two–button fiber-optic response box. Participants were instructed to maintain focus and respond with both accuracy and speed. Trials began with a central fixation cross displayed for 500 ms, followed by two sequentially presented operands (500 ms for numerical and spatial arithmetic, 200–2400 ms for temporal arithmetic) separated by a 500 ms interstimulus interval (ISI). After the second operand, a probe stimulus (500 ms for numerical and spatial arithmetic, 450–1600 ms for temporal arithmetic) appeared, prompting participants to judge whether it represented the correct result of the preceding operation. A question mark cue then signaled participants to respond via button press ("correct" or "incorrect"), with no feedback provided. Trials were separated by a jittered intertrial interval (2–4 s, mean = 3 s). An overview of the experimental procedure can be found in Fig. 1 below.

2.3. MRI data acquisition

Structural and functional MRI data were acquired at the Brain Research Institute of Guizhou Normal University using a Siemens Prisma 3 T scanner (Siemens, Erlangen, Germany) equipped with a 32–channel head coil. Stimuli were visually presented on an MRI–compatible display (refresh rate 60 Hz; resolution 1920 × 1080 pixels) and were viewed through a mirror attached to the head coil of the MRI scanner. Earplugs were used to reduce scanner noise, and neck support with foam padding minimized head movement. Behavioral responses were recorded via a two–button fiber–optic device.

During MRI acquisition, functional images were acquired with a T2*–weighted gradient–echo EPI sequence using a 1000 ms repetition time (TR), 32 ms echo time (TE), 80° flip angle, 192 × 192 mm field of view (FOV) and 64 × 64 matrix to collect 34 contiguous axial slices (3.5 mm thickness) at 3 × 3 × 3 mm resolution. Structural (T1) data were collected by a high–resolution three–dimensional magnetization–prepared rapid gradient echo (MPRAGE) sequence with a 2530 ms TR, 1.94 ms TE, 7° flip angle, 192 × 192 mm FOV and a 192 × 192 matrix to collect 176 sagittal slices (1 mm thickness) at 1 × 1 × 1 mm resolution.

2.4. Preprocessing

Preprocessing of the fMRI data was performed in MATLAB R2021a (The MathWorks, Natick, MA, USA) using SPM12 (http://www.fil.ion.ucl.ac.uk/spm, Ashburner and Friston, 2000) and included slice-timing correction, realignment to the first volume of each run (yielding six motion parameters), and co-registration of the high-resolution T1–weighted anatomical image to the mean functional image. Tissue segmentation using Montreal Neurological Institute (MNI) probability maps classified voxels as gray matter, white matter, or CSF, and the resulting deformation fields were applied to normalize functional images to MNI space at 3 × 3 × 3 mm resolution. Finally, normalized

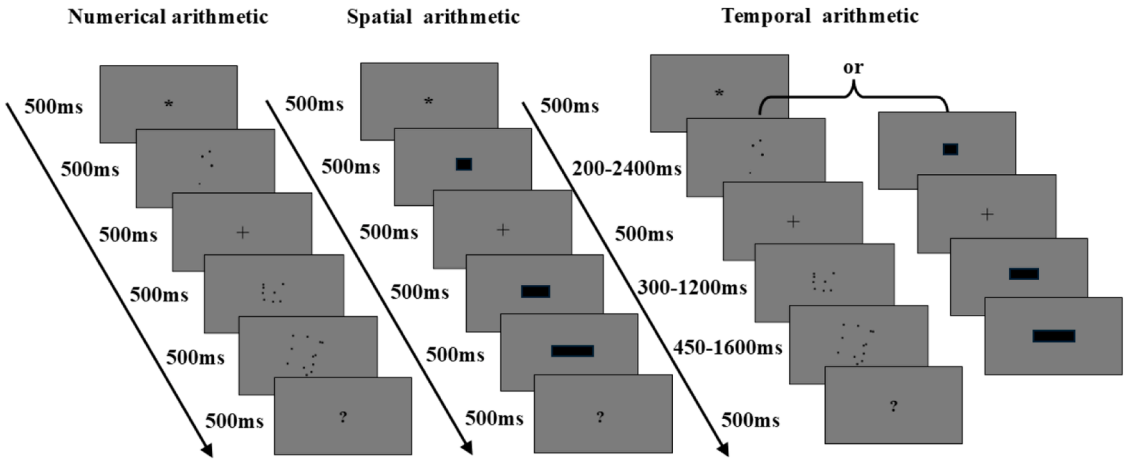

Fig. 1. Overview of the three magnitude arithmetic tasks. Participants were asked to judge whether a probe stimulus matched the sum (addition) or difference (subtraction) of two sequentially presented dot arrays (numerical arithmetic), length (spatial arithmetic) and duration (temporal arithmetic).

volumes were smoothed with an 8 mm full width at half-maximum Gaussian kernel.

To evaluate head motion during fMRI scanning, we computed framewise displacement (FD) based on the six realignment parameters. The mean FD across all participants was 0.066 mm (range: 0.041–0.127 mm), indicating minimal motion throughout the sessions.

2.5. Individual level analysis

At the individual (fixed–effects) level, task–evoked activity during the prediction and outcome intervals was characterized by convolving event onset vectors with the canonical hemodynamic response function within a general linear model (GLM). In this model, onset times were defined as the presentation times of the first operand, second operand, and probe stimulus, with event durations set to 0 s. This resulted in nine task-related regressors that were time-locked to the onset of three types of magnitude–based arithmetic operations across different arithmetic stages: numerical (first operand, second operand, probe stimulus), spatial (first operand, second operand, probe stimulus), and temporal (first operand, second operand, probe stimulus). Six head motion parameters were included as nuisance regressors. Each task regressor—-spanning prediction and outcome phases—was convolved with the canonical hemodynamic response function to form the GLM's design matrix. A high–pass filter (128 s cutoff) removed low–frequency drifts, and temporal autocorrelations were accounted for using a first–order autoregressive model.

2.6. Group level analysis

For the group–level analysis, we first conducted conjunction analyses to identify regions commonly engaged across all three magnitude domains, using the nine task–related regressors derived from the first–level models. We then performed a voxel–wise 3 (magnitude dimension: number, space, time) × 3 (arithmetic stage: first operand, second operand, probe stimulus) flexible factorial ANOVA in SPM12 to characterize domain–specific activation.

First, in the conjunction analysis, we tested the following contrasts at each arithmetic stage, including numerical arithmetic–first operand ∩ spatial arithmetic–first operand ∩ temporal arithmetic–first operand, numerical arithmetic–second operand ∩ spatial arithmetic–second operand ∩ temporal arithmetic–second operand, numerical arithmetic–probe stimulus ∩ spatial arithmetic–probe stimulus ∩ temporal arithmetic–probe stimulus. Each conjunction identifies voxels that are significantly active across all three tasks at the corresponding stage. All analyses employed second–level random–effects models and were based on t–statistics. Statistical significance was assessed using a voxel–wise threshold of $p < 0.001$ combined with a cluster–level family–wise error (FWE) correction at $p < 0.05$.

Second, for the voxel–wise ANOVA, this factorial analysis tested the main effects of task, main effects of stage, and interactions. We focused on the interaction effects to reveal regions showing differential activation patterns across magnitude domains. Statistical significance was assessed using a voxel–wise threshold of $p < 0.001$ and a cluster–level FWE correction at $p < 0.05$.

2.7. Functional connectivity analysis

To examine task–modulated changes in functional connectivity, we conducted seed–to–voxel generalized psychophysiological interaction (gPPI) analyses using the CONN toolbox (Functional Connectivity Toolbox; https://www.conn–toolbox.org, Whitfield–Gabrieli and Nieto–Castanon, 2012). Prior to the preprocessing, each participant's first–level GLM was imported into the CONN toolbox to extract their structural and task–based fMRI data. Seed regions were defined based on the core neural substrates of the magnitude system, including bilateral IPS, SMA, insula and IFG (Cona et al., 2024; Skagerlund et al., 2016), and were selected from CONN's built–in seed templates.

Functional MRI data were denoised within the CONN toolbox using a comprehensive nuisance regression approach. The model included: (1) the six head motion parameters and their first–order temporal derivatives; (2) one–hot regressors representing scrubbed volumes identified by ART; (3) five principal components of signals from white matter and cerebrospinal fluid (aCompCor); and (4) linear and quadratic drift terms. After regression, the residuals were bandpass–filtered (0.008–0.09 Hz) to restrict the analysis to the low–frequency BOLD signal range. Denoising quality was assessed using diagnostic plots of residual autocorrelation and spectral density.

At the individual level, the design matrix included task–related regressors for each event type, including numerical (first operand, second operand, probe stimulus), spatial (first operand, second operand, probe stimulus), and temporal (first operand, second operand, probe stimulus). These were generated by convolving condition–specific onset timings with the canonical hemodynamic response function (HRF). The BOLD time series extracted from each seed region served as the physiological regressor, and interaction terms representing the product of this time series and each task regressor were included as PPI regressors. To account for potential confounds, the model also incorporated six nuisance parameters reflecting participant head motion and scanner–related drift. At the group level, magnitude dimension (number, space, time) and arithmetic stage (first operand, second operand, probe stimulus) interaction was calculated. Statistical significance was determined using a voxel–wise threshold of $p < 0.001$ and a cluster–level FWE correction at $p < 0.05$.

2.8. ROI analysis

To investigate condition–specific activation and connectivity effects, each cluster showing significant interactions between magnitude dimension and arithmetic stage in the whole-brain ANOVA or functional connectivity analyses was defined as a region of interest (ROI) for subsequent analyses. Beta values for each experimental condition were extracted using MarsBaR (Ashburner and Friston, 2000). A follow–up 3 (magnitude dimension: number, space, time) × 3 (arithmetic stage: first operand, second operand, probe stimulus) repeated–measures ANOVA was performed on the extracted ROI signals to assess condition–specific activation differences. Greenhouse–Geisser corrections were employed when the sphericity assumption was violated, and Bonferroni–adjusted post hoc tests were conducted to account for multiple comparisons.

3. Results

3.1. Behavioral results

To ensure comparability across conditions, two separate repeated–measures ANOVAs were conducted on reaction times (RTs) and accuracy (ACC) for the temporal, spatial, and numerical arithmetic tasks. A summary of the behavioral data is presented in Table 1. A repeated-measures ANOVA on mean RTs across the three conditions revealed a significant effect of task, F (2, 28) = 9.27, $p < 0.01$, $\eta^2 = 0.398$. Three paired-samples t-tests—Bonferroni-corrected—showed no difference between numerical and spatial arithmetic ($p = 0.837$), but significant differences between numerical and temporal arithmetic ($p = 0.023$) and between spatial and temporal arithmetic ($p < 0.001$). The

Table 1
Behavioral data of the magnitude arithmetic task.

	Reaction times (ms)		Accuracy (%)	
	RT	SD	Acc	SD
Numerical Arithmetic	592	307	79.55	6.02
Spatial Arithmetic	547	210	78.33	6.09
Temporal Arithmetic	704	218	73.25	8.78

repeated-measures ANOVA on accuracy revealed no significant effect of task, F (2, 28) = 0.24, p = 0.789, η^2 = 0.017, indicating comparable performance across magnitude domains.

3.2. Conjunction analyses results

Conjunction analyses identified brain regions that were activated across all three tasks at each arithmetic stage (see Fig. 2 and Table 2). In the first operand stage, all three tasks conjointly activated bilateral superior parietal lobule (SPL), IPL, Insula, precentral gyrus, and SMA. In the second-operand stage, convergent activation was observed in the left IPL, precentral gyrus, calcarine sulcus, SMA, and right insula. In the probe stimulus stage, all three tasks showed overlapping activation in the bilateral IPL and SPL, the left SMA, the precentral gyrus, and the right insula and IFG.

3.3. Whole–brain ANOVA results

A 3 (magnitude dimension: number, space, time) × 3 (arithmetic stage: first operand, second operand, comparison) voxel–wise ANOVA revealed significant interactions in bilateral middle occipital gyrus (MOG), left superior occipital gyrus (SOG) and left precentral gyrus (see Fig. 3 and Table 3). Further ROI analysis showed that bilateral MOG and left SOG showed stronger activation for the numerical and spatial tasks than for the temporal task during the first operand and probe stages, whereas the left precentral gyrus exhibits higher activation for temporal arithmetic than numerical or spatial arithmetic during the first and second operand stages, but showed lower activity during the probe stimulus stage.

3.4. Functional connectivity results

Seed–to–voxel functional connectivity analysis revealed distinct connectivity patterns for the different arithmetic domains. After a 3 (magnitude dimension: number, space, time) × 3 (arithmetic stage: first operand, second operand, comparison) ANOVA, significant interactions were observed in the bilateral IPS. Specifically, when using the left IPS as seed region, significant interactions can be found in the left inferior occipital gyrus (IOG), bilateral precentral gyrus, and left cerebellum. Similarly, with the right IPS as seed region, significant interactions appeared in bilateral precentral gyrus and left cerebellum (see Fig. 4 and Table 4).

Further ROI analysis of these connectivity clusters indicated that temporal arithmetic was associated with significantly greater functional coupling between bilateral IPS and bilateral precentral gyrus and left cerebellum compared to numerical or spatial arithmetic across different arithmetic stages. By contrast, the numerical and spatial tasks produced stronger connectivity between left IPS and left IOG in the first operand and probe stimulus stages.

4. Discussion

The aim of the present study was to investigate whether arithmetic over magnitudes in the spatial, temporal, and numerical domains engages a shared operational network or instead relies on domain–specific mechanisms. To answer these questions, we utilized an fMRI paradigm

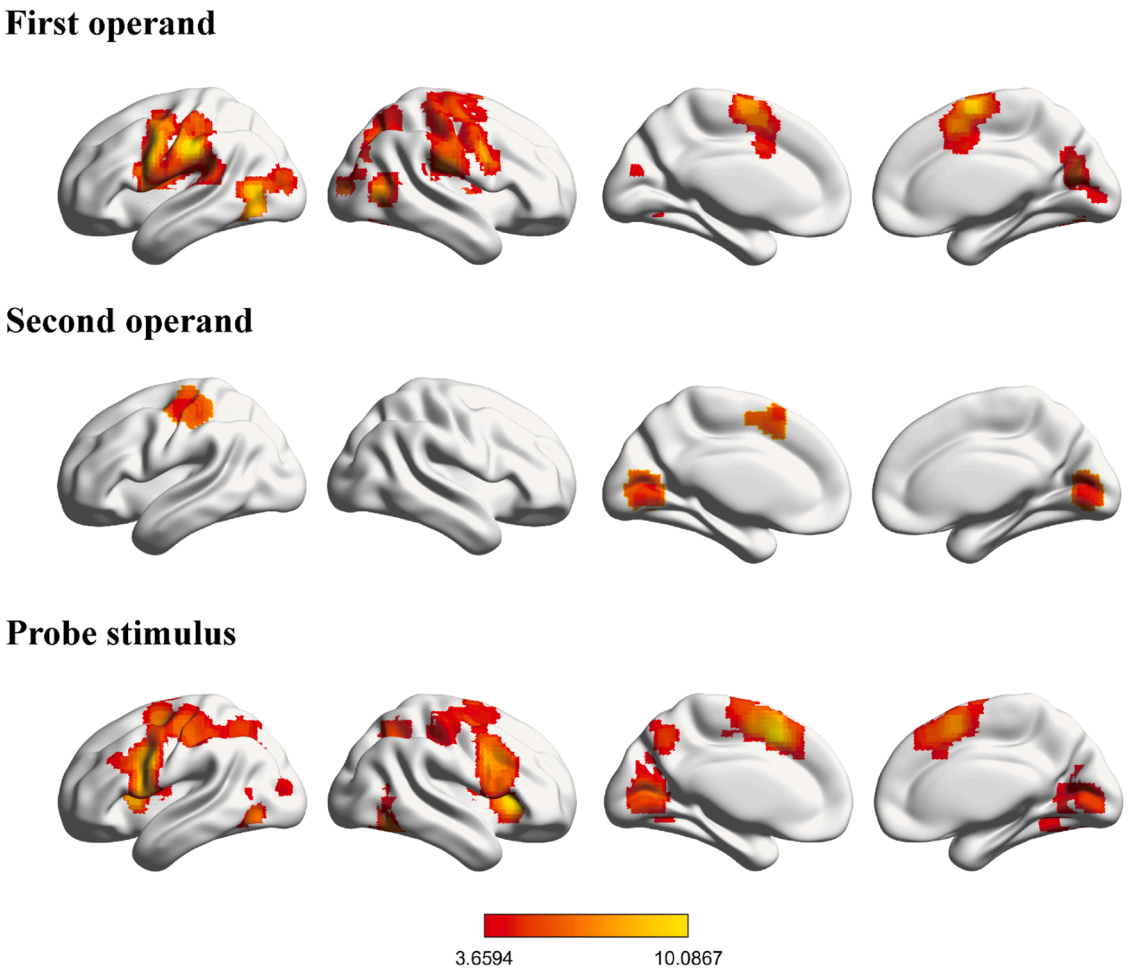

Fig. 2. Regions of overlap activations between temporal, spatial and numerical arithmetic in the first operand, second operand and probe stimulus stage.

Table 2
Overlapping clusters identified in the conjunction analysis.

Arithmetic stage	Cluster	Coordinates	Brain Region	Brodmann Area
First operand				
	1179	−54 5 38	Precentral Gyrus	6
		33 −34 53	Inferior Parietal Lobule	40
		−51 11 23	Inferior Frontal Gyrus	44
		39 −1 8	Insula	13
	1026	55 11 32	Precentral Gyrus	6
		33 −43 53	Inferior Parietal Lobule	40
		51 11 23	Inferior Frontal Gyrus	44
		−39 4 17	Insula	13
	638	30 −61 53	superior parietal lobule	7
	368	3 −1 62	SMA	6
	64	−24 −58 53	superior parietal lobule	7
Second operand	287	−18 −70 5	Calcarine	17
		6 −76 5	Calcarine	17
	198	−27 −22 62	Precentral Gyrus	6
	38	−3 17 56	SMA	3
	22	36 −13 11	Insula	13
	129	−54 −49 41	Inferior Parietal Lobule	40
Probe stimulus	3905	33 23 5	Insula	13
		57 14 17	Inferior Frontal Gyrus	45
		−51 5 29	Precentral Gyrus	6
		51 8 41	Precentral Gyrus	6
		−27 −61 50	superior parietal lobule	7
		−33 −46 38	Inferior Parietal Lobule	40
	100	30 −49 57	superior parietal lobule	7
		33 −46 50	Inferior Parietal Lobule	40

to examine the common and specialized neural substrates of temporal, spatial, and numerical arithmetic. We found a set of brain regions conjointly activated across all magnitude dimensions, thus highlighting the core magnitude network. However, we also found that numerical and spatial arithmetic differ from temporal arithmetic in both activation and connectivity patterns. Below, we discuss these findings in the context of shared and distinct magnitude processing.

4.1. A common system of magnitude arithmetic

The first aim of the study was to identify brain regions common to temporal, spatial, and numerical arithmetic, thereby revealing whether a shared operational network exists. We found overlapping activation in the IPL, SPL, insula, precentral gyrus, SMA, and IFG during the first operand and probe stimulus stages, and in the IPL, precentral gyrus, calcarine sulcus, SMA, and insula during the second–operand stage. These results align with prior studies examining neural activity associated with processing spatial, temporal, and numerical information (Cona et al., 2024; Skagerlund et al., 2016). However, their findings primarily examined the processing of single magnitude information; our results extend this pattern of neural overlap to mental arithmetic, which requires the manipulation of multiple successive magnitudes.

During the processing of the first operand and probe stimulus, we observed overlapping activations in the IPL, SPL, insula, precentral gyrus, SMA, and IFG. Functionally, the IPL and SPL surrounding the IPS act as a supra–modal hub for magnitude representation (Bhatia et al., 2022; Bueti and Walsh, 2009; Hawes et al., 2019) and are crucial for mental arithmetic by supporting magnitude comparison, alignment, and the updating of intermediate results (Chang et al., 2019; Dormal et al., 2014; Liu et al., 2017). The insula serves as a domain–general control hub that detects salient internal and external changes, switches among large–scale networks, and allocates resources to optimize task performance; it does not execute arithmetic operations directly but monitors conflict and signals control demands (Menon et al., 2020). The SMA contributes to externally guided, sensory–driven actions and integrates multiple spatial reference frames (Cona et al., 2021; Cona and Semenza, 2017; Skagerlund et al., 2016). The IFG underlies categorical, decision–based representations of magnitude conveyed via the dorsal visual stream (Skagerlund et al., 2016). According to the ATOM, these regions comprise a distributed magnitude processing system (Cona et al., 2021, 2024; Skagerlund et al., 2016). Notably, we also found significant precentral gyrus activation across all tasks—an effect not emphasized by ATOM but likely reflecting the heightened sensorimotor demands of arithmetic versus passive magnitude judgments (Youssofzadeh et al., 2023). Finally, consistent with McCrink et al. (2007), who emphasized that processing the first operand and probe stimulus in numerical operations involves attentional anchoring and magnitude comparisons on the MNL, our results suggest that temporal and spatial arithmetic likewise recruit brain regions supporting these attentional anchoring and magnitude comparison processes during the first operand and probe stimulus stages, thereby extending McCrink's account beyond numerical to temporal and spatial arithmetic.

During the processing of the second operand, we observed overlapping activations in the IPL, precentral gyrus, calcarine, SMA and insula As noted above, the IPS–adjacent IPL supports the abstract representation of magnitude information; the SMA integrates sequential elements into higher–order structural representations; the insula detects salient shifts, orchestrates network transitions, monitors conflict, and allocates resources; and the precentral gyrus reflects the sensorimotor demands of mental arithmetic. Notably, the calcarine sulcus—part of primary visual cortex (V1)—exhibits spatially specific activation corresponding to the locus of attention in visual tasks (Somers et al., 1999). In the magnitude processing, it underlies internal visual "replay" or "scanning" operations and is engaged whenever positions along the MNL are imagined or scanned (Cattaneoet al., 2009; Fornaciai et al., 2017). Thus, these regions not only constitute core nodes of the magnitude–processing network but also participate in MNL–based attentional and sensorimotor operations. Based on these findings, we predict that during the second–operand stage: the insula and IPS first identify magnitude and tag its salience; the precentral gyrus and SMA mediate directional attention shifts and internal motor simulations along the mental number line; and the calcarine sulcus provides visual–spatial support. Through the coordinated activity of these regions, attention shifts along the mental number line are implemented.

In summary, our results confirm that time, space, and number share a common operational network–one that supports multi step operations beyond the encoding of single magnitudes–and demonstrate that magnitude based mental arithmetic engages both visuospatial processes (e.g., spatial mapping) and sensorimotor processes (e.g., attentional shifting). One potential confound is that the same arithmetic paradigm was used across all three magnitude tasks to assess whether they rely on a common processing system. However, this design also raises the possibility that the overlapping activations reflect domain–general executive demands—such as working memory and cognitive control—rather than magnitude–specific processing. Although we minimized sustained maintenance requirements by using brief, single–operation trials, we cannot entirely rule out the contribution of such general processes. Future studies should therefore incorporate explicit control conditions that systematically vary executive load without engaging magnitude–specific operations, to better separate domain–general control mechanisms from magnitude–related processing.

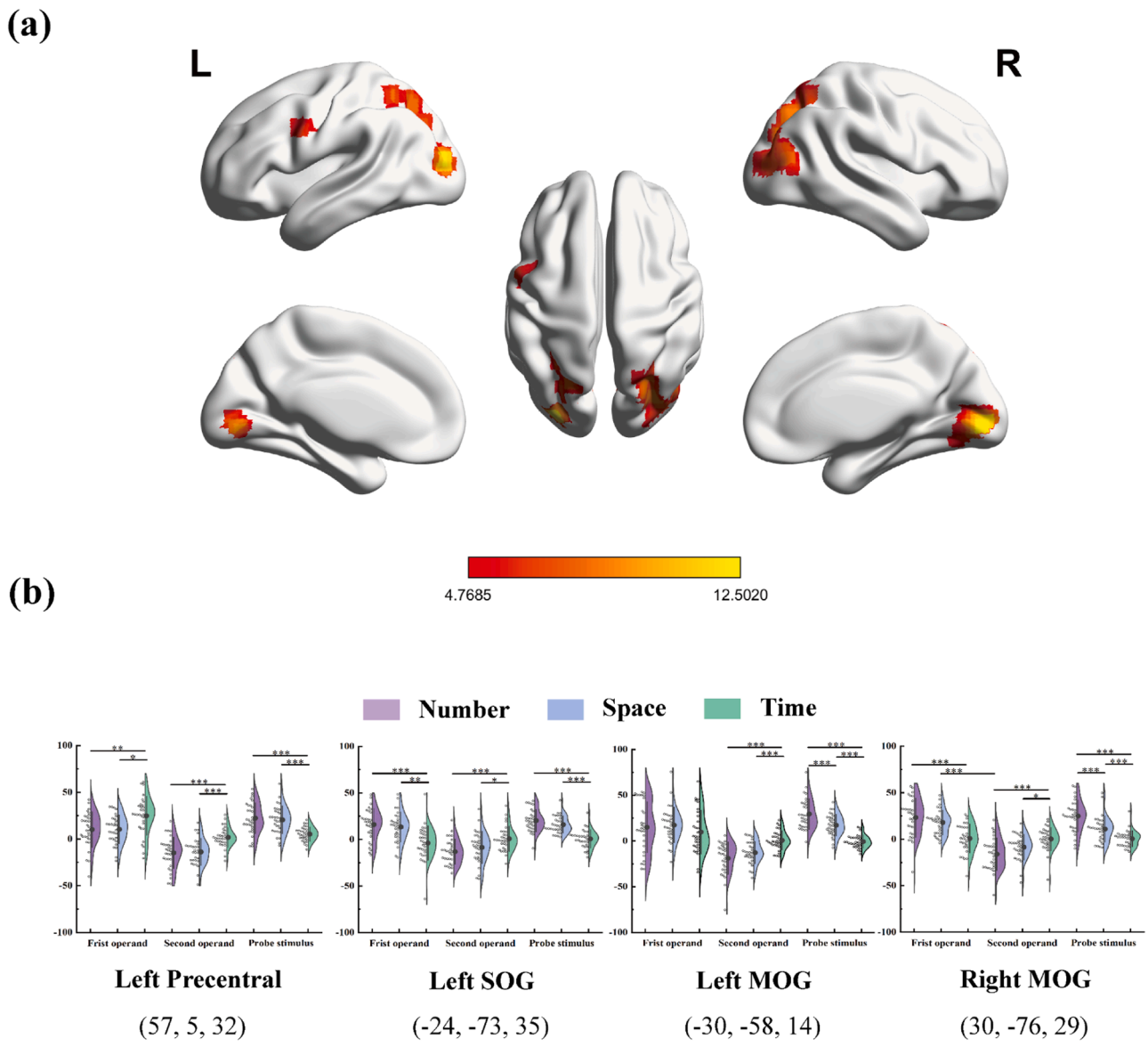

Fig. 3. (a) Brain activation in response to significant interactions of magnitude dimension and arithmetic stage; (b) ROI analysis of each condition.

Table 3
Clusters identified significant interactions between magnitude dimension and arithmetic stage.

Cluster	Coordinates	Brain Region	Brodmann Area
443	30 −76 29	Middle occipital gyrus	19
96	−24 −73 35	Superior occipital gyrus	19
72	−30 −85 14	Middle occipital gyrus	19
33	57 5 32	Precentral Gyrus	6

4.2. Specialized neural pathway of magnitude arithmetic

Another issue to consider is whether the common system of time, space, and number is fully integrated or partly specialized. We found that spatial and numerical arithmetic differ from temporal arithmetic in both activation and connectivity patterns. Specifically, numerical and spatial arithmetic showed greater activation in the left IOG and bilateral SOG, whereas temporal arithmetic elicited stronger activation in the left precentral gyrus. Functional-connectivity analyses using the left IPS as a seed region further demonstrated that numerical and spatial arithmetic exhibited significantly greater connectivity with the left IOG, while temporal arithmetic showed stronger connectivity from bilateral IPS to the precentral gyri and the cerebellum. These results indicate that temporal arithmetic relies on a distinct processing mechanism, implying that the magnitude system is only partially shared.

The IOG and SOG are crucial nodes of the visual association cortex (VAC), jointly subserving the early stages of visual processing by encoding elementary features and integrating global spatial configurations and motion cues to support scene analysis and object recognition (Fernández et al., 2023). In magnitude processing, this cortex dynamically modulates spatial attention in proportion to stimulus magnitude (Hwang et al., 2020; Kido et al., 2025) and bias contralateral excitability along the MNL (Casarotti et al., 2007; Fischer and Knops, 2014). For example, transforming dot arrays or geometric shapes into a "magnitude" recruits occipital–parietal networks to construct spatial magnitude estimates (Van Rinsveld et al., 2021). This pattern is consistent with an occipital–parietal coupling mechanism, in which the IPS exerts top–-down spatial biases that reconfigure occipital representations to provide precise visuospatial input for higher–order magnitude comparisons (Lefco et al., 2020). Park et al. (2013) similarly demonstrated that performing arithmetic on dot arrays increases functional coupling between PPC and VAC, reflecting the need to map visual numerosity onto a

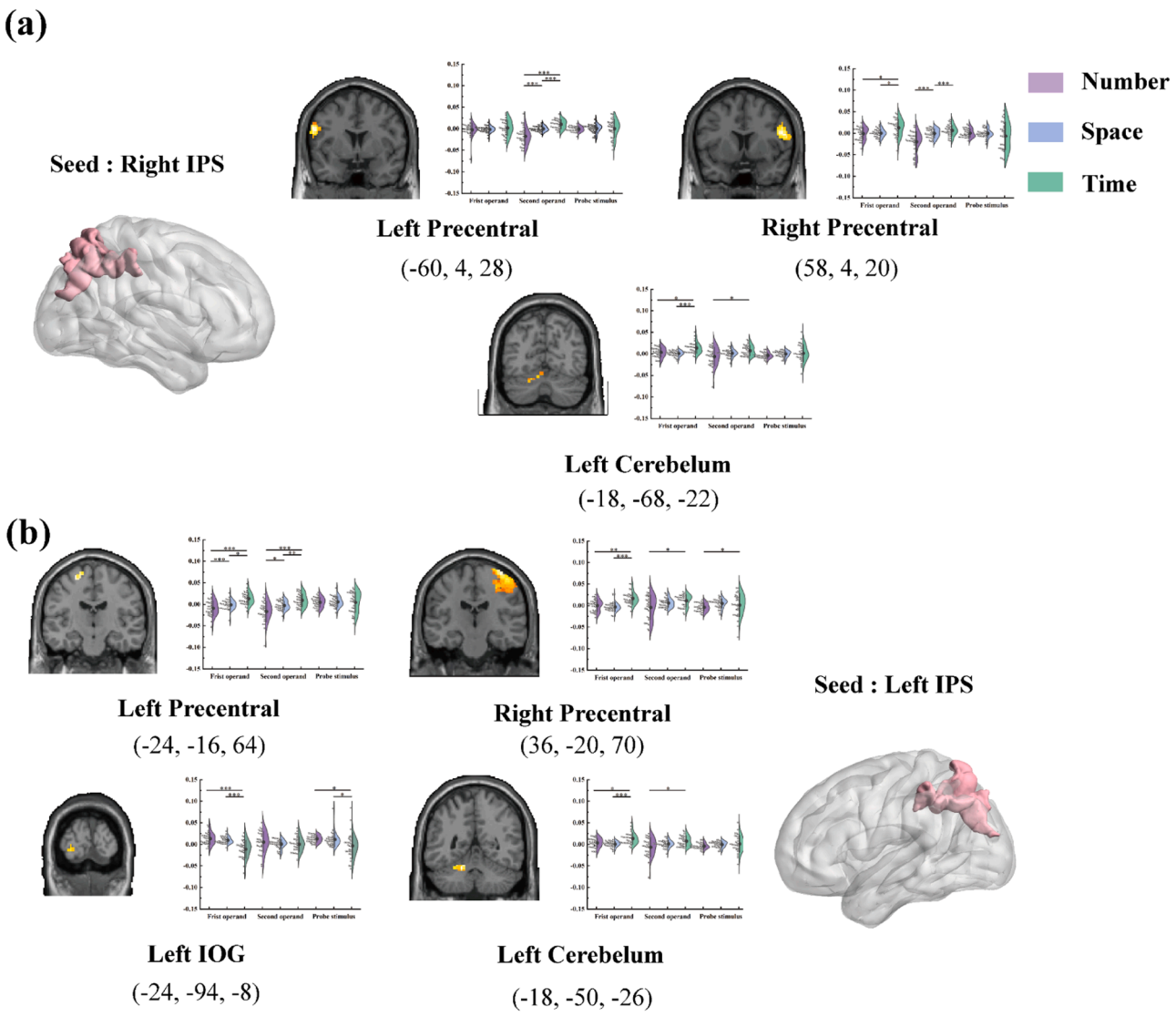

Fig. 4. (a) For the right IPS, a significant interaction between magnitude dimension and arithmetic stage was observed in the left cerebellum and bilateral precentral gyrus. (b) For the left IPS, a significant interaction between magnitude dimension and arithmetic stage was found in the left IOG, left cerebellum, and bilateral precentral gyrus.

Table 4
Brain regions with significant interactions between magnitude dimension and arithmetic stage for functional connectivity analysis as the seed region of the bilateral IPS.

Seed region	Cluster	Coordinates	Brain Region	Brodmann Area
Right IPS	336	58 4 20	Precentral Gyrus	4
	248	−60 4 28	Precentral Gyrus	4
	106	−18 −68 −22	Cerebellum	N/A
Left IPS	1344	36 −20 70	Precentral Gyrus	6
	105	−18 −50 −26	Cerebellum	N/A
	96	−24 −94 −8	IOG	18
	80	−24 −16 64	Precentral Gyrus	4

magnitude scale. According to Dehaene (1999), numerical arithmetic relies on visuospatial mechanisms, which involve transforming magnitudes into spatial formats and performing analog operations through hierarchical processing between the PPC and VAC. Therefore, stronger activation of IOG and SOG and enhanced coupling between IPS and IOG observed during numerical and spatial arithmetic suggest that these operations rely more on early visuospatial networks to optimize magnitude discrimination than temporal arithmetic does.

The precentral gyrus, a component of the primary motor cortex (PMC), translates external sensory inputs into motor plans (Ehrsson and Chancel, 2019), whereas the cerebellum utilizes sensory prediction errors to fine–tune temporal precision and optimize movement dynamics (Johnson et al., 2019); both regions reflect core sensorimotor processing. In magnitude processing, these areas subserve temporal perception and, together with the IPS, constitute the core network underpinning temporal magnitude processing (Bueti et al., 2008.; Carver et al., 2012; Schubotz et al., 2000). For example, Schubotz et al. (2000) demonstrated that both temporal perception (event sequencing and duration estimation) and motor timing (action planning) activate the PMC, cerebellum, and IPS; they further proposed that the PMC subserves abstract temporal encoding, the lateral cerebellum maintains fine–grained timing calibration, and the IPS underpins supra–modal sequence representation. Bueti et al. (2008) reported that duration discrimination reliably recruits the IPS, SMA, PMC, and cerebellar regions, underscoring their integral role in converting temporal percepts into action. Park et al. (2013) demonstrated functional connectivity between the right IPS and left sensorimotor cortex in the numerical tasks, independent of overt motor responses, suggesting a sensorimotor mechanism, such as covert finger counting or subvocal enumeration, that facilitates

the transformation of visual numerical information into action–based representations. Therefore, stronger activation of PMC and cerebellum, along with enhanced coupling between IPS and PMC during temporal arithmetic, suggests that, compared with spatial and numerical operations, temporal arithmetic relies more heavily on sensorimotor mechanisms that support internal simulation and monitoring of dynamic temporal information.

Taken together, these findings support a partial sharing model of magnitude processing. A common core network—including the IPS, SMA, insula, and IFG—is recruited across all arithmetic tasks, reflecting domain–general magnitude processing. Superimposed on this core, two specialized streams are differentially engaged depending on the nature of the magnitude: numerical and spatial arithmetic recruit occipito–parietal visuospatial networks, whereas temporal processing engages parietal–sensorimotor networks. Importantly, these networks do not operate in isolation. For example, temporal tasks still elicited IPS activation and functional connectivity with the occipital cortex, while spatial tasks activated the SMA and insular hubs. Such intermixing is expected, as all magnitude judgments ultimately require abstract comparison and response selection. Nevertheless, differences in brain activation and IPS coupling with distinct networks under varying task demands highlight the flexible configuration of the magnitude system—it can dynamically route information through visual circuits for static magnitudes or through motor circuits for dynamic, time–based magnitudes.

4.3. Partly shared systems for static versus dynamic magnitude

In summary, our study reveals a partially shared system for processing time, space, and number in mental arithmetic. Within this network, numerical and spatial processing depend on visuospatial mechanisms, whereas temporal processing relies on sensorimotor mechanisms. Notably, space and number exhibit predominantly static characteristics, as they can be apprehended in a single visual snapshot and are supported by rapid feedforward encoding of extrinsic features such as texture, boundaries and contours within the visual cortex, eliminating the need for sequential processing (Bolaños et al., 2024). However, temporal attributes possess inherently dynamic properties: these stimuli evolve continuously over time or across spatial positions, and their perception requires the integration and accumulation of sequential information, rendering instantaneous, single–time–point processing insufficient (Schoffelen et al., 2024). Taken together with the inherently static nature of number and space and the dynamic nature of time, our findings suggest that magnitude processing may rely on two distinct subsystems: a visuospatial pathway for static magnitude, and a sensorimotor pathway for dynamic magnitude.

Previous research has documented the reliance of numerical and spatial processing on visuospatial mechanisms. For example, the arithmetic cueing effect shows that after solving addition problems, participants respond faster to visual targets presented in right space, whereas after solving subtraction problems, they respond faster to targets presented in left space, indicating that numerical arithmetic engages visuospatial mechanisms, with operations acting as directional cues for spatial orienting (Prado and Knops, 2024). Similarly, the Operational Momentum (OM) effect reveals that arithmetic operations are mentally simulated as spatial shifts, supporting the involvement of visuospatial dynamics in numerical cognition (McCrink et al., 2007; Prado and Knops, 2024). These findings suggest that numerical arithmetic is reliably supported by visuospatial mechanisms, underscoring the close association between numerical and spatial processing (Fischer and Shaki, 2014). According to "Neuronal Recycling Hypothesis" proposed by Dehaene & Cohen (2007), shared mechanisms between number and space originate from the evolutionary repurposing of visuospatial circuits—originally developed for sensorimotor interactions with the environment and later recycled to support culturally acquired numerical skills (Dehaene and Cohen, 2007; Hawes et al., 2019).

Although the role of sensorimotor processes in magnitude cognition has received relatively little attention, it may nonetheless support a broad class of operations involving dynamically varying magnitudes (Anobile et al., 2021; Bollini et al., 2021; Piazza et al., 2006). For example, Piazza et al. (2006) employed alternating visual and auditory sequences and showed that the right IPS and bilateral precentral gyrus are involved in marking and integrating discrete events into unified numerical representations, suggesting that the PMC supports supra–modal magnitude accumulation. Similarly, Bollini et al. (2021) used a stimulus–response compatibility paradigm—comparing low–left/high–right mappings in auditory versus vibrotactile tasks under uncrossed and crossed hand postures—and found that tactile compatibility reverses with hand crossing, indicating that tactile magnitude judgments recruit body–centered sensorimotor circuits. Anobile et al. (2021) further proposed a dedicated "sensorimotor numerosity system" demonstrating that humans engage sensorimotor mechanisms when estimating either external stimuli or their own actions.

Collectively, these findings suggest that, like visuospatial networks, sensorimotor networks have also been co–opted to support numerical cognition. dynamic magnitude processing—such as temporal arithmetic—may rely on the continuous accumulation of sequentially presented events, a process analogous to the neural mechanisms underlying motor planning and sequence control. Given their role in planning and monitoring sequential actions, premotor circuits are well suited to support event accumulation or continuous counting. It is plausible that circuits originally dedicated to sensorimotor integration, by virtue of their spatiotemporal tuning, provide a neural foundation for processing dynamic magnitudes, which may explain why temporal arithmetic in our study preferentially engaged sensorimotor networks.

Notably, the neural substrates involved in temporal processing vary with interval duration: millisecond–range timing depends more heavily on cerebellar and sensorimotor regions, whereas suprasecond intervals recruit parietal and fronto–striatal networks more prominently. Future studies should systematically manipulate interval length to determine whether subsecond and suprasecond arithmetic rely similarly on sensorimotor networks, or whether longer intervals additionally engage alternative systems such as visuospatial circuits. Such work would help clarify the cognitive and neural architecture of dynamic magnitude processing and its connection to static magnitude representations.

In the present study, all magnitude types activated core regions of the magnitude system. However, static magnitudes, including number and space, preferentially engaged visuospatial networks, whereas dynamic magnitudes, specifically time, were more strongly associated with sensorimotor networks. These findings suggest that the magnitude system comprises at least two functionally distinct subsystems: a static processing stream that relies on visuospatial networks and a dynamic stream that depends on sensorimotor networks. This partly shared architecture likely enhances neural efficiency by repurposing evolutionarily established circuits, explaining why time, space, and number recruit overlapping substrates while also exhibiting domain–specific specializations. Our results provide a potential explanatory framework for the developmental shift in magnitude processing. This framework proposes that the magnitude system, which is more fully shared in childhood, progressively differentiates into domain–specialized networks with cognitive maturation, eventually transforming into a partially shared system in adulthood. Future longitudinal studies should examine the critical period for this differentiation and its underlying influencing factors.

5. Conclusion

Our findings demonstrate that numerical, spatial, and temporal arithmetic rely on a partially shared system. Within this framework, the IPS, SMA, insula, and IFG function as a shared magnitude hub, encoding supra–modal representations common to all magnitude types. Superimposed on this core, static magnitudes, such as number and space, are

processed via occipital–parietal visuospatial networks, whereas dynamic magnitudes, especially temporal information, are processed through a sensorimotor pathway involving the PMC and cerebellum. In summary, our results indicate that the brain's magnitude system is neither fully unified nor wholly segregated but instead comprises a distributed network with a shared core and domain–specific modules. This reconceptualization encourages a paradigm shift by integrating static and dynamic dimensions into a unified framework, informs future theories of cognitive architecture, and guides the development of targeted interventions for disorders of magnitude perception.

Ethics approval and consent to participate

All participants provided written informed consent prior to participation, and all procedures were performed in compliance with relevant laws and institutional guidelines and were approved by the Committee for the Protection of Human Subjects at the School of Psychology, Guizhou Normal University (approval number: PSY.N.202404E [0015]; approval date: 15 April 2024), in accordance with the Declaration of Helsinki.

Conflict of interest

The authors declare that this study was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Data accessibility

All original code and reported data can be found at https://www.scidb.cn/s/mieaAr. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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CRediT authorship contribution statement

Liangzhi Jia: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Zhiwei Zhang:** Writing – review & editing. **Chengtao Wang:** Writing – review & editing. **Yuanyi Liu:** Writing – review & editing. **Fangwen Yu:** Supervision. **Di Zhang:** Supervision. **Yun Pan:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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