

Peoples' friendship University of Russia Named after Patrice Lumumba

As a manuscript

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**METACOGNITION IN THE STRUCTURE OF MATHEMATICAL
COGNITION: A COGNITIVE AND NEURAL NETWORK ANALYSIS**

5.3.1. General Psychology, Personality Psychology, History of Psychology

Thesis
for the PhD degree in Psychology

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Moscow - 2026

Федеральное государственное автономное образовательное учреждение
высшего образования «Российский университет дружбы народов имени
Патриса Лумумбы»

На правах рукописи

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**МЕТАКОГНИЦИИ В СТРУКТУРЕ МАТЕМАТИЧЕСКОГО
ПОЗНАНИЯ: КОГНИТИВНЫЙ И НЕЙРОСЕТЕВОЙ АНАЛИЗ**

5.3.1. Общая психология, психология личности, история психологии
(психологические науки)

Диссертация

на соискание ученой степени
кандидата психологических наук

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INTRODUCTION

Relevance of the research. Contemporary research in cognitive psychology suggests that the effectiveness of cognitive activity is determined not only by the level of development of basic cognitive functions, but also by the individual's capacity to monitor and regulate their own thought processes. These functions are realized through a system of metacognitive processes, including awareness of the course of thinking, evaluation of task difficulty, monitoring of solution accuracy, and regulation of the allocation of cognitive resources. The theoretical foundations of metacognition were laid in the works of J. Flavell (1979) and were subsequently elaborated in the models of metacognitive monitoring and control proposed by Nelson (1996), as well as in contemporary cognitive and neurocognitive studies [46].

Metacognition assumes a particularly important role in the domain of mathematical cognition, which constitutes one of the most complex forms of intellectual activity. The solution of mathematical problems requires the integration of multiple cognitive processes, including operations on symbolic information, quantitative analysis, working memory, executive control, and the selection of problem-solving strategies. Under such conditions, metacognitive monitoring enables the individual to assess the degree of task difficulty, modify solution strategies, and regulate the expenditure of mental effort [171]. As demonstrated in the studies of Garofalo and Lester (1985) [50], as well as Mevarech (1995), metacognitive processes exert a significant influence on students' success in mathematical activity and represent an important factor in the development of mathematical thinking.

Behavioral studies convincingly demonstrate that the level of development of metacognitive skills constitutes one of the most significant determinants of success in mathematics learning. Metacognitive interventions enable students to recognize the structure of a problem, monitor the course of their reasoning, and identify errors in a timely manner, thereby substantially increasing the effectiveness of mathematical problem solving [35,114,138]. Moreover, metacognitive regulation is

regarded as a key mechanism underlying the formation of autonomous cognitive activity and the development of problem-solving strategies.

Despite the considerable body of research devoted to metacognition and mathematical thinking, these lines of inquiry have, to a large extent, developed independently of one another. Within cognitive psychology, metacognition has traditionally been studied primarily in the context of perception, memory, and decision-making processes [34, 35, 144, 172], whereas research on mathematical cognition has focused on the mechanisms of numerical processing, quantitative representations, and symbolic operations [33, 83, 181]. As a consequence, the problem of the interaction between metacognitive monitoring and the processes underlying mathematical thinking remains insufficiently investigated.

Of particular interest is the phenomenon of subjective mental effort, which may be considered one of the key indicators of metacognitive monitoring. The assessment of expended effort reflects the subjective perception of task difficulty and the current state of cognitive resources, while also serving as a signal for the regulation of subsequent cognitive activity. Contemporary studies indicate that the subjective evaluation of effort is associated with processes of cognitive control, uncertainty monitoring, and resource allocation [71, 125, 129].

The development of neuroimaging methods has substantially expanded the possibilities for investigating the functional organization of cognitive processes. The use of functional magnetic resonance imaging makes it possible to examine the dynamics of brain activity during the performance of cognitive tasks and to relate these dynamics to different aspects of cognitive functioning. Existing studies indicate that metacognitive processes rely on the interaction of distributed systems of cognitive control and self-referential processing [144, 67, 147], whereas mathematical thinking is associated with the activation of frontoparietal networks supporting numerical processing and problem solving [83]. However, the principal significance of such studies lies not in the description of isolated neural structures, but rather in the refinement of our understanding of the functional organization of cognitive processes and the mechanisms underlying their interaction.

Notwithstanding the substantial progress achieved in the study of metacognition and mathematical cognition, there remain no studies in which these processes have been examined within a unified experimental paradigm. In particular, insufficient attention has been devoted to the question of how the metacognitive evaluation of subjective mental effort relates to processes of mathematical processing and which functional mechanisms mediate their interaction.

Thus, the relevance of the present study is determined by the need for a comprehensive analysis of the interaction between metacognitive processes of monitoring and control and the cognitive mechanisms underlying mathematical thinking. Investigation of this problem makes it possible to deepen the understanding of the structure of human cognitive activity, to clarify the role of metacognition in the regulation of thinking, and to contribute to the further development of contemporary cognitive-psychological models of mathematical cognition.

The state of research on the problem

The interaction between metacognition and mathematical cognition has become an important topic in contemporary cognitive psychology and cognitive neuroscience. However, existing research has developed largely along two relatively independent lines: the study of the cognitive mechanisms underlying mathematical thinking, and the analysis of metacognitive monitoring and control.

Research on mathematical cognition has shown that numerical processing and arithmetic problem solving rely on a distributed frontoparietal brain network, in which the intraparietal sulcus (IPS) plays a central role by supporting the representation of numerical magnitude and the execution of calculation-related operations [83]. Several studies have also demonstrated the involvement of lateral frontal regions and temporal cortical areas, which support the symbolic processing of numerical information and the retrieval of arithmetic facts from long-term memory [109, 66].

Within metacognition research, particular attention has been devoted to uncertainty monitoring, the evaluation of response accuracy, and the formation of subjective confidence. Studies by Jiang et al. (2022) and Li et al. (2022) indicate that

metacognitive monitoring depends critically on medial and lateral regions of the prefrontal cortex, including the dorsal anterior cingulate cortex, the dorsomedial prefrontal cortex, and the lateral frontopolar cortex. These structures are regarded as key components of the cognitive control system responsible for evaluating one's own cognitive processes and regulating behavior.

Recent neuroimaging studies further suggest that when metacognitive judgments—such as confidence ratings or estimates of error likelihood—are incorporated into mathematical and logical tasks, additional activation is observed in brain systems associated with metacognitive processing. This finding points to a functional interaction between computation and monitoring processes [67, 83]. At the same time, these processes are most often examined separately, which makes it difficult to identify the systemic nature of their relationship.

A range of methodological approaches has been used to investigate metacognitive processes. One of the most common involves tasks followed by confidence judgments or error-probability estimates, which make it possible to analyze changes in cognitive activity as a function of both objective accuracy and subjective evaluation of performance [67, 89]. Another approach is based on computational models of metacognitive sensitivity and efficiency derived from signal detection theory and dynamic evidence-accumulation models [18]. In addition, there is growing interest in studies that integrate data from multiple neuroimaging methods in order to examine the structural and functional organization of cognitive processes [66, 83].

In recent years, considerable attention has also been paid to cross-domain studies of metacognition. Comparative evidence suggests that metacognitive monitoring may include both domain-general and domain-specific components. For example, Bellon et al. (2020) show that, in the course of development, metacognitive abilities gradually acquire a more general character and extend across different cognitive domains. At the same time, studies by Jiang et al. (2022) and Li et al. (2022) point to differences between self-reflective metacognition and the

mechanisms involved in understanding other people's mental states (mentalizing), highlighting the complex hierarchical organization of metacognitive processes [59].

A separate line of research has addressed individual differences in metacognitive accuracy and their association with emotional and cognitive factors [94, 95, 196], including mathematics anxiety and specific features of cognitive control [151, 130, 66, 174].

Despite the substantial body of accumulated evidence, the current state of research is characterized by several important limitations:

- most existing studies examine metacognitive processes primarily in perceptual or memory tasks, whereas their role in more complex forms of intellectual activity, such as mathematical thinking, remains insufficiently understood;
- the indicators of metacognition used across studies vary considerably - including confidence ratings, calibration indices, and signal-detection-theory-based measures - which complicates comparison across findings [109, 18, 127].
- a large proportion of the available evidence is correlational in nature, which limits the interpretation of causal mechanisms linking metacognitive and cognitive processes [66, 67].

Thus, despite persuasive evidence for the role of metacognitive processes in the regulation of cognitive activity, and despite substantial progress in the study of the neural foundations of mathematical thinking, the interaction between metacognitive monitoring and mathematical cognition remains insufficiently investigated. To date, there have been no empirical studies in which these processes have been systematically examined within a unified experimental paradigm capable of directly comparing the mechanisms of mathematical processing and metacognitive evaluation.

This theoretical and empirical gap defines the **central research problem** of the present study, which is aimed at investigating the interaction between metacognitive monitoring of mental effort and processes of mathematical cognition.

Key unresolved questions include:

1. Whether metacognitive monitoring during mathematical problem solving relies on domain general metacognitive hubs or exhibits domain specific tuning within mathematical circuits.
2. How subjective mental effort - a metacognitive judgment - is neurally instantiated and how it relates to objective task difficulty and arithmetic performance.
3. Whether mathematical operations (addition, subtraction, multiplication, division) and difficulty levels differentially recruit overlapping metacognitive networks.
4. The lateralization patterns of metacognitive versus mathematical processing and their functional significance.

The present dissertation addresses these gaps by employing fMRI to directly compare neural activation during arithmetic problem solving and subsequent effort rating metacognitive tasks, thereby providing the first empirical evidence of shared and distinct neural substrates for mathematical cognition and metacognitive monitoring.

Objective of the study – is to identify and empirically substantiate the nature of the interaction between metacognitive processes of monitoring and control and the processes underlying mathematical thinking, as well as to determine their functional organization using neuroimaging methods.

Research object – metacognition and mathematical cognition.

The subject of the study is the cognitive mechanisms underlying the interaction between metacognitive monitoring (in the form of mental effort assessment) and mathematical cognition while solving arithmetic problems of varying complexity.

Research hypotheses:

General Hypothesis

1. Metacognitive monitoring of mental effort and mathematical cognition constitute interrelated yet functionally distinct levels of the cognitive organization of activity. Mathematical computation is assumed to operate at the level of object-

level cognitive processes, whereas metacognitive mechanisms are responsible for monitoring, evaluating task difficulty, and regulating task performance. This integration can be conceptualized within a two-level architecture, where **Level 1** corresponds to mathematical processing (object level), and **Level 2** corresponds to metacognitive monitoring and control (meta-level).

Specific Hypotheses

1. Metacognitive monitoring and mathematical cognition are hypothesised to rely on partially overlapping cognitive control mechanisms. Specifically, the assessment of mental effort and the resolution of mathematical problems are hypothesised to engage common systems for monitoring and regulating cognitive activity.

2. The cognitive processes involved in mathematics are dependent on both domain-specific information-processing mechanisms and domain-general cognitive control systems. The resolution of mathematical problems necessitates the implementation of specialized processes for the management of quantitative and symbolic information.

3. Task difficulty parametrically modulates the engagement of metacognitive monitoring. Increases in objective difficulty lead to greater activation of cognitive control systems and higher subjective ratings of mental effort.

4. Different arithmetic operations (addition, subtraction, multiplication and division) recruit distinct cognitive processing strategies. Corresponding differences in their functional neuroanatomy should be evident.

5. The hemispheric organisation of mathematical cognition and metacognitive evaluation differs. While mathematical processing is expected to demonstrate more pronounced left-hemispheric specialisation, metacognitive monitoring is likely to exhibit a more bilateral pattern.

Achieving the set goal requires solving the following **tasks**:

1. To review theoretical models of metacognition and mathematical cognition, identifying key approaches to their functional organization and interrelation.

2. To synthesize current perspectives on metacognitive monitoring, focusing on subjective mental effort as a cognitive regulation mechanism.
3. To design and implement an experimental paradigm for a direct, within-subject comparison of mathematical problem-solving and subsequent effort evaluation.
4. To empirically investigate how arithmetic operation type and task difficulty influence the functional organization of mathematical cognition.
5. To identify the cognitive and neural correlates of metacognitive monitoring and determine their overlap and differentiation from those of mathematical processing.
6. To interpret the results within contemporary frameworks of metacognition and mathematical thinking, clarifying the interaction between these processes.

Theoretical and methodological Framework of the work is based on the following scientific principles: 1) The principle of the unity of consciousness and activity (182, 195) enabled the study of the neural correlates of cognitive processes during the performance of mathematical and metacognitive tasks; 2) The principle of determinism provided a rationale for investigating the neurological foundations of cognitive processes; 3) Based on the principle of psychophysical unity, metacognitive and cognitive processes are considered inseparably connected to their neurological correlates [65, 132]. The following metacognitive theories were used as the theoretical framework of the study: Flavell's Model (1979): Metacognition is viewed as "cognition about cognition," involving monitoring and control of one's own cognitive processes, Nelson's Model (1990): Distinguishes between an object-level (task performance) and a meta-level [self-evaluation], which monitors and controls the object level; Signal Detection Theory & Metacognitive Efficiency: Confidence and performance judgments are modeled as metacognitive sensitivity (meta- d'), separating monitoring accuracy from task performance; Bayesian & Probabilistic Frameworks: Metacognitive judgments are treated as second-order inferences about the reliability of first-order decisions, linking to computational

models of uncertainty [10, 74]; Control-Theoretic Perspective: Metacognition is embedded in closed-loop regulation, where monitoring signals (e.g., effort, uncertainty) inform control decisions (e.g., effort allocation, strategy selection) [60, 165] and also Mathematical Cognition Theories [128]: Triple Code Model (Dehaene& Cohen): Proposes three distinct but interacting neural systems for number processing: analogue magnitude, visual-Arabic, and verbal codes; Approximate Number System : An evolutionarily older system for non-symbolic numerosity, providing a foundation for symbolic mathematical learning; Domain-General Resource Models: Mathematical performance relies on working memory, executive functions, attentional control, and cognitive load management. This research is grounded in an integrative theoretical framework that bridges cognitive neuroscience, educational psychology, and computational modeling.

Materials and Methods

In accordance with the aim of the study and the proposed hypotheses, the following methods were employed:

1. Theoretical analysis. A theoretical analysis of the scientific literature on metacognition, subjective mental effort, mathematical cognition, and their neural correlates was conducted.

2. Experimental method. The empirical study was carried out using functional magnetic resonance imaging (fMRI). During scanning, participants were presented with blocks of arithmetic tasks varying in operation type (addition, subtraction, multiplication, and division) and difficulty level, as well as control tasks involving comparison of the fonts of visually presented numbers. The control condition was included to account for basic visual-perceptual and decision-making processes.

Each experimental block contained mathematical and control trials. Task difficulty was manipulated by varying the number of digits in the operands. After each mathematical block, participants completed a metacognitive evaluation by rating the subjective mental effort experienced during task performance. Each evaluation period was followed by a fixation interval. Thus, the experimental cycle included mathematical task performance, metacognitive evaluation, and rest.

Primary data acquisition was performed at the National Research Centre “Kurchatov Institute” (Moscow) using a Siemens Magnetom Verio 3T MRI scanner. Functional images sensitive to blood-oxygen-level-dependent (BOLD) signal changes were acquired using a standard echo-planar imaging (EPI) protocol.

3. fMRI data preprocessing and statistical analysis. Preprocessing of functional and anatomical data was conducted using the AFNI software package and included slice timing correction, head motion correction, coregistration of functional and anatomical images, spatial normalization to MNI space, spatial smoothing, and masking of non-brain tissues.

Statistical analysis was performed within the framework of the general linear model (GLM) at both the individual and the group level. The analysis included regressors corresponding to mathematical tasks, metacognitive evaluation, control conditions, and fixation baseline, with head motion parameters entered as nuisance regressors. Contrasts of interest were computed to identify neural activity associated with metacognitive evaluation, mathematical processing, and differences across arithmetic operations and levels of task difficulty.

At the group level, random-effects analysis was performed, with correction for multiple comparisons applied in accordance with accepted standards of fMRI research. In addition, a region-of-interest (ROI) analysis was conducted for statistically significant activation clusters in order to characterize BOLD signal dynamics and determine their anatomical localization [154].

Empirical sample

Twenty young, healthy adults participated in the study (10 women, 10 men) with an average age of 23.85 years. All participants were right-handed. Exclusion criteria included left-handedness, failure to complete a pre-screening number matching task, and extreme performance (either very high or very low) on a parametric mathematical problem during behavioral screening. Participants were asked to fill in a screening form and sign a consent form for counterindications testing.

The validity and reliability of the research's main provisions, results and conclusions are ensured by the thorough theoretical and methodological development of the problem; adherence to fundamental methodological and logical-scientific principles; compliance with accepted standards of theoretical and empirical psychological research; the representativeness of the sample; and the use of validated statistical data processing methods appropriate to the study's purpose, subject and tasks. The substantial volume of analysed and systematised theoretical material, along with the high degree of generalisation underlying the logic of constructing the empirical investigation, attests to the reliability and scientific validity of the study's results and conclusions.

The most significant and novel research results obtained personally by the author, and their scientific novelty:

1. The study develops an integrative cognitive model of the interaction between metacognitive monitoring and mathematical cognition. Within this model, the subjective evaluation of mental effort is conceptualized as a key mechanism in the regulation of cognitive activity. Mental effort is shown to perform a dual function: on the one hand, it reflects the outcome of monitoring ongoing cognitive processes; on the other hand, it serves as a regulatory signal guiding the allocation of cognitive resources and the selection of problem-solving strategies.

2. The empirical findings demonstrate that metacognitive and mathematical processes rely on partially overlapping cognitive mechanisms responsible for monitoring, difficulty evaluation, and cognitive control. This makes it possible to substantiate the view of metacognition as an integrative component of mathematical activity rather than as a process external to it.

3. At the same time, the study establishes the existence of functional differentiation between metacognitive monitoring and mathematical processing. Mathematical cognition is shown to involve domain-specific mechanisms for the processing of symbolic and quantitative information, which distinguishes it from more general metacognitive processes of monitoring and regulation.

4. The results provide empirical support for the validity of subjective ratings of mental effort as a metacognitive indicator of cognitive load. These ratings were found to vary systematically as a function of the engagement of cognitive control systems during the solution of mathematical problems of differing levels of difficulty.

5. A parametric relationship was identified between the objective difficulty of mathematical problems and the recruitment of metacognitive monitoring mechanisms. This finding indicates that metacognitive processes are embedded in the structure of mathematical thinking and play an active role in the regulation of cognitive performance.

6. The study yields new data on the functional organization of mathematical cognition by demonstrating that different arithmetic operations—addition, subtraction, multiplication, and division—are associated with specific cognitive strategies and distinct activation profiles within the broader system of mathematical processing.

7. The findings also reveal differences in the hemispheric organization of metacognitive and mathematical processes. In particular, mathematical cognition was found to display predominantly left-hemispheric specialization, whereas metacognitive monitoring was characterized by a more bilateral pattern of functional organization.

Thus, the scientific novelty of the study lies in the development of a theoretically grounded and empirically supported account of the interaction between metacognitive monitoring and mathematical cognition, in clarifying the regulatory role of subjective mental effort, and in extending current understanding of the functional organization of complex cognitive activity.

The theoretical significance of the present study is determined by its contribution to the further development of cognitive-psychological conceptions of the structure, mechanisms, and regulation of human cognitive activity.

– The study contributes to the integration of two major areas of contemporary psychological research—metacognition and mathematical

cognition—which have traditionally developed as relatively autonomous fields of inquiry. The results obtained make it possible to substantiate the position that metacognitive monitoring should not be regarded as a process external to mathematical thinking. On the contrary, it constitutes an immanent regulatory mechanism embedded in the structure of mathematical activity itself and ensuring the evaluation of task difficulty, the coordination of cognitive resources, and the adjustment of problem-solving strategies.

– The study refines existing theoretical approaches to metacognitive monitoring and control by specifying the functional status of subjective mental effort. The findings demonstrate that the subjective evaluation of effort should be understood not merely as a phenomenological correlate of perceived difficulty, but as a substantive metacognitive mechanism that reflects the current state of cognitive load, mediates the monitoring of task demands, and participates in the regulation of further cognitive activity. In this respect, the study expands current theoretical conceptions of the internal mechanisms through which cognitive regulation is achieved.

– The results contribute to the elaboration of theoretical views on the functional organization of mathematical thinking. The findings indicate that mathematical cognition is not reducible to domain-specific operations on numerical and symbolic information alone. Rather, it should be conceptualized as a multi-component and hierarchically organized system in which specialized mathematical processing is closely linked to mechanisms of monitoring, evaluation, and control. Such an interpretation makes it possible to clarify the place of metacognitive processes within the general structure of mathematical activity and to describe mathematical problem solving as a form of cognitively regulated intellectual performance.

– Of particular theoretical importance is the two-level model of cognitive activity substantiated in the study. Within this model, mathematical cognition is interpreted as the object-level of task-related information processing, whereas metacognitive monitoring is treated as the meta-level responsible for the evaluation

and regulation of cognitive performance. The proposed model deepens the theoretical understanding of the relationship between thinking and self-regulation and provides a conceptual basis for the further development of theories of metacognition, cognitive control, and reflective organization of intellectual activity.

– The study also contributes to the discussion concerning the domain-general and domain-specific nature of metacognitive processes. The findings support the view that metacognitive monitoring relies on relatively general mechanisms of cognitive control, while at the same time varying as a function of the structural characteristics and operational demands of a particular cognitive domain [183]. This makes it possible to regard metacognition as a domain-general regulatory system whose concrete realization depends on the specific features of the activity in which it is engaged, including mathematical problem solving.

– The results enrich contemporary theoretical conceptions of cognitive self-regulation by demonstrating that subjective mental effort occupies a central position in the architecture of monitoring and control. It functions as an internal indicator of the current state of cognitive resources and, at the same time, as a regulatory mechanism ensuring the adaptive reorganization of activity under conditions of changing task demands.

Thus, the theoretical significance of the study lies in the fact that it expands and refines current scientific understanding of the interaction between metacognitive and mathematical processes, clarifies the role of metacognition in the regulation of mathematical thinking, and contributes to the further development of contemporary cognitive-psychological models of thinking, self-regulation, and complex intellectual activity.

The practical significance of the dissertation is determined by the possibility of applying its findings in educational practice, psychological diagnostics, and scientific-methodological support of research and instruction.

The results of the study may be used in the development of educational programs aimed at fostering metacognitive competencies in learners. The data obtained provide a basis for designing interventions directed toward the

development of skills of self-monitoring, evaluation of task difficulty, regulation of mental effort, and conscious selection of effective problem-solving strategies in the course of mathematical activity.

The findings may be applied in the field of educational psychology and the methodology of mathematics instruction. In particular, they make it possible to improve approaches to mathematics teaching by incorporating methods aimed not only at the acquisition of subject knowledge and procedural skills, but also at the development of reflective and self-regulatory forms of cognitive activity. Consideration of subjective assessments of mental effort may contribute to the optimization of instructional design, the differentiation of learning tasks, and the enhancement of students' effectiveness in solving mathematical problems.

The results have practical relevance for the development of adaptive educational technologies and digital learning environments. The established relationships between subjective effort evaluation and mathematical performance make it possible to construct systems that take into account not only the objective parameters of task difficulty, but also the learner's current cognitive state. Such an approach is particularly important in work with students who experience persistent difficulties in mathematics or display elevated levels of mathematics anxiety.

The findings may be used for the development and refinement of diagnostic instruments intended to assess metacognitive monitoring, effort regulation, and cognitive control in academic contexts. The results of the study may therefore be employed in psychological assessment aimed at identifying individual differences in self-regulatory functioning, predicting learning effectiveness, and determining the factors that influence the success of performance in cognitively demanding tasks.

The materials and conclusions of the dissertation may be applied in scientific and methodological work devoted to the study of cognition, metacognition, and self-regulation, and may serve as a basis for further interdisciplinary research at the intersection of cognitive psychology, educational science, and cognitive neuroscience. In this regard, the study contributes not only to the accumulation of

empirical knowledge, but also to the improvement of methodological approaches to investigating the relationship between cognitive and metacognitive processes.

Thus, the practical significance of the study lies in its potential for application in educational, diagnostic, and research practice, as well as in the possibility of using its findings to improve instructional methods, develop adaptive learning technologies, and design tools for the assessment and support of self-regulation in cognitive activity.

The research stages

At the **theoretical-methodological stage**, a systematic analysis of the scientific literature was conducted on metacognition, subjective mental effort, mathematical cognition, and their neural correlates identified through functional magnetic resonance imaging (fMRI). This analysis made it possible to define the study's theoretical framework, substantiate its conceptual foundations, and formulate hypotheses concerning both the common and the functionally specific mechanisms underlying metacognitive monitoring and mathematical cognition. At the same stage, the experimental paradigm was developed in accordance with the study's aim and objectives, the procedures for stimulus presentation and behavioral response recording were programmed, ethical approval was obtained, and the participant sample was recruited.

At the **experimental stage**, behavioral screening was carried out in order to verify participants' compliance with the inclusion criteria. The main empirical study was then conducted in accordance with the predefined experimental design. Primary data acquisition was performed at the National Research Center "Kurchatov Institute" (Moscow) using a Siemens Magnetom Verio magnetic resonance imaging scanner. The experimental design made it possible, within a unified paradigm, to compare the processes involved in solving arithmetic problems of varying levels of difficulty and in the subsequent metacognitive evaluation of expended mental effort.

At the **data processing and analysis stage**, functional neuroimaging data were preprocessed using the AFNI (Analysis of Functional NeuroImages) software package. Statistical analysis was then performed within the framework of the general

linear model (GLM), at both the individual and the group level. This stage was aimed at identifying the functional correlates of mathematical processing and metacognitive monitoring, as well as determining the degree of overlap and differentiation between them.

At the **final interpretive and generalizing stage**, the results obtained were interpreted in the context of the research hypotheses and contemporary theoretical approaches to metacognition, cognitive control, self-regulation, and mathematical cognition. Based on these findings, the dissertation chapters were prepared. The research results were also reflected in scientific publications and presented in reports at international academic conferences.

Provisions Submitted for Defense

1. Metacognitive monitoring and mathematical cognition constitute interrelated yet functionally distinct levels of the organization of cognitive activity. Mathematical problem solving is implemented at the object-level of information processing, whereas metacognitive processes operate at the meta-level, providing monitoring, evaluation of task difficulty, and regulation of cognitive performance.
2. Metacognitive monitoring of mental effort relies on relatively domain-general mechanisms of cognitive control. These mechanisms are engaged both in metacognitive evaluation and in the solution of mathematical tasks, indicating a functional integration of regulatory and task-related components of cognitive activity.
3. Mathematical cognition is characterized by domain-specific mechanisms for processing quantitative and symbolic information. These mechanisms complement the operation of more general systems of cognitive control and determine the specific features of mathematical information processing.
4. The subjective evaluation of mental effort constitutes a valid and theoretically significant metacognitive indicator of cognitive load. It reflects the current state of cognitive resources and serves as a regulatory signal involved in the

allocation of effort during the solution of mathematical problems of varying difficulty.

5. The involvement of metacognitive monitoring mechanisms increases parametrically with the objective difficulty of mathematical tasks. This indicates that metacognitive processes are embedded in the structure of mathematical thinking and play an active role in the regulation of cognitive activity.
6. Different arithmetic operations are associated with different cognitive strategies and distinct functional profiles within the general system of mathematical cognition. This confirms the internal differentiation of mathematical processing and demonstrates that arithmetic activity cannot be reduced to a single uniform mechanism.
7. Metacognitive monitoring and mathematical cognition differ in their hemispheric organization. Mathematical processing is characterized by more pronounced left-hemispheric specialization, whereas metacognitive monitoring displays a more bilateral pattern of functional organization.

Approbation of the results

The main theoretical propositions and empirical results of the study were discussed at methodological seminars held at the Department of Psychology and Pedagogy of the Faculty of Philology, Peoples' Friendship University of Russia (RUDN University), and were presented at scientific conferences of various levels, including:

- the International Scientific and Practical Conference “Experimental and Theoretical Research in Modern Science” (Moscow, 2026);
- the 19th International Scientific and Practical Conference “Higher Education: Experience, Problems, and Prospects. Personality in the Educational Space” (Moscow, RUDN University, 2026);
- the 13th International Scientific and Practical Conference “Society, Science, Practice” (Kyrgyz-Russian Slavic University, Bishkek, 2026).

The results of the study are reflected in six scientific publications by the author, including two articles published in leading peer-reviewed journals recommended by the Academic Council of the Peoples' Friendship University of Russia (in accordance with the Regulations on Awarding Academic Degrees of RUDN University, approved on February 19, 2018), and two articles published in journals indexed in the Scopus scientometric database.

Compliance of the dissertation with the research field passport

The thesis corresponds to the following items of the research field passport 5.3.1. General Psychology, Personality Psychology, and History of Psychology: №7. The psychophysical problem; №8. Consciousness and cognitive processes. Cognitive psychology; №9. Thinking, imagination. Emotional-semantic regulation of thinking. Practical thinking in complex systems. Metacognitions, their role in the regulation of human behavior and activity; №17. Consciousness. States of consciousness. Reflective processes. Thinking and thought processes: structure, types, and research methods.

Structure and Scope of the Dissertation. The thesis consists of an introduction, 2 chapters, a conclusion, a list of references and supplementary material. The main text of the thesis is set out on 122 pages. The list of references includes 205 sources, of which 164 are in English. The thesis contains 122 tables and 28 figures. The volume of the text as a whole is 204 pages.

CHAPTER 1. THEORETICAL AND FUNCTIONAL FOUNDATIONS OF THE INTERACTION BETWEEN METACOGNITION AND MATHEMATICAL COGNITION

1.1. Metacognition and Subjective Mental Effort in the Structure of Cognitive Regulation

"Meta," a Greek word meaning "after" is added to terms such as metamemory and metacognition [110]. However, these are just examples of the use of "meta". The term "meta" is added to a wide range of words such as meta-attributions, meta-analysis and metapsychology among other. There is a vast array of definitions regarding the higher cognitive function of metacognition. According to Nelson (1996), the object level of cognition is represented by metacognition, a model of cognition that operates at a meta level, whereas for Brown (1987), metacognition is referred to as being aware of and in control of one's own cognitive system. Furthermore, for Schraw and Sperling-Dennison (1994) metacognition is the capacity to consider, comprehend, and regulate one's own learning. One of the earliest and most popular definitions is Flavell's (1979) who sees metacognition as a combination of cognition and knowledge about one's own cognitive processes [180]. It is argued that Plato was the first to refer to the awareness of one's own thoughts [51] in his dialogue Meno, where Plato anticipates the concept of metacognition by sharing the cognitive self (the aspect of one's self-concept that includes one's ideas, convictions, and self-knowledge) into three distinct identities: "student," "teacher," and "evaluator" [155]. However, it was the ancient philosopher Aristotle who laid the groundwork for the concept of metacognition, pointing out that the mind has capacities beyond sight and hearing, such as being aware of its own workings, such as thoughts and emotions [51].

One of the earliest and most significant examinations of introspection in Western literature is found in Montaigne's Essays, which were originally published in 1580. In the context of metacognition, Montaigne's essays are especially important because of his unrelenting investigation of his own ideas, convictions, and experiences. He uses the essay format to investigate and comprehend his own thoughts, approaching his writing as a kind of self-examination [161].

Coming to the 17th century AC and the Enlightenment era in Europe, Rene Descartes' famous statement, "Cogito, ergo sum" (I think, therefore I am), and his method of doubt mark a turning point in the development of self-reflection and philosophy of mind. by highlighting the self-evident truth of one's existence as a thinking entity [161]. This statement captures the essence of metacognition.

Metacognition is now typically defined as the capacity to monitor and control one's own cognitive processes. Metacognition -“cognition about cognition”- is typically decomposed into monitoring (online evaluation of cognitive states such as confidence, feelings of knowing, and uncertainty) and control (regulation of strategies, effort, persistence, and cognitive offloading) and operates on metacognitive knowledge, experiences, and skills across domains such as memory, perception, reasoning, and learning [17, 46, 189]. Monitoring involves forming second-order representations of performance, confidence, and uncertainty, while control refers to strategy selection, allocation of cognitive resources, and decisions to persist, switch, or offload tasks to the environment [22].

Clinical and developmental models extend this view by emphasizing multilevel, higher-order capacities for integrating information about self and others, as well as the role of metacognition in co-regulation within social interactions [26, 88, 131].

Higher-order / introspectionist theories views hold that metacognition arises when a mental state [e.g., a perceptual decision] is the target of a distinct higher-order representation [199]. On this picture, confidence or awareness depends on the availability of such higher-order states, which encode the probability that the first-order state is correct and make it accessible to report and voluntary control [44]. These theories explain why some internal processes remain unconscious (no higher-order representation) while others are available to introspection and also naturally link metacognitive monitoring to explicit error awareness and verbal report [20].

Mindreading/ self-interpretation accounts argue that human metacognition largely reuses mechanisms for attributing mental states to others; we “turn mindreading on ourselves” and interpret our own attitudes from behavior, context, and partial internal cues [28].

Key claims are that:

- Access to one's own propositional attitudes is interpretive rather than introspective.

- Developmental and comparative data (e.g., partial metacognitive abilities in non-human animals, dissociations in autism and schizophrenia) are better explained if metacognition piggybacks on a general theory-of-mind system [28, 140].

This view predicts that metacognitive judgments can be systematically biased, fallible, and shaped by folk-psychological theories rather than direct readout of internal evidence.

A dominant contemporary strand treats metacognition—especially confidence—as an information-processing computation over internal evidence [44].

1. Signal detection and SDT-based models
2. In a first-order task, internal evidence is modeled with sensitivity parameter d' .
3. A second-order decision (e.g., confidence) evaluates how likely the first-order response is to be correct given this evidence.
4. The construct *meta- d'* is defined as the level of first-order sensitivity needed to generate the observed confidence data if all information were optimally used; *metacognitive efficiency* is then [44].

$$M - ratio = \frac{meta - d'}{d'}$$

This framework formalizes metacognitive sensitivity (confidence–accuracy correspondence) and efficiency (monitoring quality relative to task performance) and has become standard in perceptual and memory metacognition [44].

Bayesian theories cast self-evaluation as a second-order inference about the reliability of one's own decisions. A general framework proposes that confidence is computed by a system that infers the performance of an (often idealized) decision-maker, which may be temporally or spatially distinct from the mechanisms generating first-order choices [45].

- This “other-actor” interpretation explains why metacognition can sometimes be better or worse than first-order performance.

- It unifies confidence, error detection, and related judgments as different readouts of a common probabilistic inferential process [16, 45].

Dynamic evidence accumulation models (e.g., drift–diffusion, Bayesian sampling) treat decisions as noisy accumulation of evidence to a bound, with confidence derived from the state of the accumulator and decision time. Within these models:

- Monitoring quality can be parameterized via readout noise or separate accumulation processes for confidence.

- Strategic settings (e.g., decision thresholds) and speed–accuracy tradeoffs shape both first-order performance and apparent metacognitive ability.

Recent work shows that static indices like M-ratio are systematically influenced by response caution, so that manipulating speed versus accuracy alters estimated metacognitive efficiency even when monitoring mechanisms are unchanged; dynamic metrics such as the ratio of drift rates for confidence versus primary decisions (a v-ratio-like measure) better isolate metacognitive noise from control policy [44].

These models motivate a dynamic conception of metacognition in which confidence, error awareness, and control unfold over time rather than being a fixed mapping from evidence to judgment.

From a *control-theoretic perspective*, metacognition is embedded in closed-loop regulation:

- Monitoring provides estimates of accuracy, difficulty, uncertainty, and cost [13].

- Control systems use these estimates to set thresholds, allocate effort, choose strategies, and decide whether to persist, seek help, or offload to external tools [45,178].

Computational accounts such as expected-value-of-control models formalize this by weighing anticipated gains in accuracy or reward against subjective effort costs, with metacognitive evaluations (e.g., confidence, perceived effort) feeding into these cost–benefit computations [44].

Theories of social metacognition emphasize that monitoring and control can be directed at both self and others, and that group-level regulation (e.g., in collaborative problem solving) depends on how individuals express confidence, uncertainty, and strategy proposals [80, 198]. Group-metacognition studies show that higher-performing

groups engage in richer shared monitoring and explicit strategy negotiation, indicating that metacognitive processes scale to the collective level [44].

Comparative research finds partial metacognitive abilities (e.g., opt-out choices, information seeking) in animals, raising questions about which forms of human metacognition require language, culture, or explicit mindreading [28].

Metacognition matures through childhood and adolescence in parallel with executive functions and schooling experiences; educational studies show that metacognitive knowledge and strategy use predict achievement in reading, mathematics, science, and listening comprehension, often beyond basic ability [101, 44, 170, 187]. A meta-analysis on adolescence underscores that enhancing metacognition is a promising route to improve math achievement, especially on complex tasks where self-regulation and monitoring are critical [104].

Educational work has developed domain specific instruments and interventions aimed at metacognitive regulation in mathematics and problem solving, demonstrating gains in problem solving performance and conceptual understanding [164, 104, 126].

These literatures emphasize domain specificity (e.g., reading vs mathematics strategies) and the importance of explicit instruction and practice for cultivating metacognitive skills [204].

Applied research in education shows that metacognitive knowledge and strategy use predict reading proficiency, listening comprehension, and mathematical understanding, sometimes explaining variance in performance beyond general ability [99, 168, 190, 191]. Interventions that directly train metacognitive strategies or provide metacognitive prompts (e.g., “learning is constructing” metaphors, scaffolded planning and monitoring, computer-assisted prompts) enhance students’ strategy use and can yield gains in domain-specific achievement [35, 173].

Measuring metacognition is challenging for researchers because of the difficulties encountered in pioneering and manipulating new tasks, mainly when young learners are involved in experiments [112, 169].

Beyond questionnaires and lab tasks [188], think-aloud protocols, video-based observation, and structured coding of interaction are used to capture metacognitive

regulation and shared metacognition in authentic contexts such as collaborative negotiation, classroom learning, and navigation [31]. For example, work on integrative negotiation shows that shared metacognition—explicitly aligning understandings of the task—enhances cooperation, insight into others’ preferences, and joint outcomes [31], illustrating how metacognition can operate at group as well as individual levels [26].

Across theoretical and empirical strands, current work converges on several points:

- Metacognition is multi-component, involving beliefs, online monitoring, and control processes that can be partially dissociated [44].

- Confidence and related judgments are probabilistic computations over internal evidence, but are also shaped by interpretative mindreading-like processes, prior beliefs about one’s own abilities, and motivational cost–benefit considerations [44, 28, 194].

- Metacognitive ability is partly independent of first-order performance but strongly influenced by speed–accuracy policy, affect, and incentives, demanding careful modeling and experimental control [44].

Taken together, these literatures converge on a view of metacognition as a multifaceted construct involving both online monitoring and control and offline knowledge and beliefs, operating at individual and group levels and across conscious and nonconscious processes [26, 205]. From a control-theoretic standpoint, metacognitive monitoring supplies internal state variables (e.g., uncertainty, performance estimates) that are used to determine how much control to invest. The felt effort that results from this control allocation then becomes an additional input to subsequent monitoring. Behavioral and neuroimaging studies show that instructions to “exert maximum effort” versus “relax” modulate both performance and broad fronto-parietal activation without changing objective task structure [71]. The experienced effort here is a consequence of a metacognitive decision about how intensely to engage [179]. This dual-role view aligns metacognition with a closed-loop control architecture in which effort is both a product of control engagement and a feedback signal that tunes future control policies [184].

Effort-based decision-making models propose that the brain evaluates whether to allocate control by weighing expected gains against costs of mental effort:

$$EVC = p(\text{success}) \cdot R - C(e)$$

where $p(\text{success})$ is estimated from monitoring signals (e.g., uncertainty), R indexes anticipated reward or goal value, and $C(e)$ is the subjective cost function of effort (e).

There is a claim that the most plausible examples of metacognition are included in estimates of cognitive effort [28]. According to metacognition research, students use memory functions to create a mental model of their understanding that helps them take control of their learning, however, when asserting their understanding, students should draw conclusions about their true understanding based on traits such as perceived mental load and level of effort in the learning process [125, 167].

Metacognitive judgments of confidence and difficulty rely on information about internal processing, not just external stimulus properties. One study proposes that perceived effort is one such internal cue. In perceptual and higher-order tasks, confidence and error-monitoring depend on ongoing evidence accumulation and post-decisional processing, but they also track experiences of conflict, time pressure, and difficulty, which manifest phenomenologically as “effort” [144].

From a control-theoretical standpoint, metacognitive monitoring supplies internal state variables (e.g., uncertainty, performance estimates) that are used to determine how much control to invest. The felt effort that results from this control allocation then becomes an additional input to subsequent monitoring. Over time, people use memories of prior effort costs to update their expectations about future tasks, shaping strategy selection, willingness to persist, and cognitive offloading decisions [164]. This dual-role view aligns metacognition with a closed-loop control architecture in which effort is both a product of control engagement and a feedback signal that tunes future control policies.

Across theoretical, neuroimaging, and psychophysiological literatures, mental effort emerges as a central construct that links metacognitive monitoring and control:

- As a monitoring signal, effort reflects internal estimates of difficulty, uncertainty, and conflict, encoded in dACC/dmPFC, insula, and related networks, and made available—partially—to conscious awareness [39, 68].

- As a control variable, effort reflects deliberate allocation of cognitive resources implemented by lateral and frontopolar prefrontal regions, guided by EVC-like computations integrating expected rewards and costs [71, 68].

A mature theory of “neuroimaging of metacognition” will likely treat mental effort not as a nuisance variable to be controlled away, but as a primary object of study—a dynamic signal that is both the product and driver of metacognitive processes

1.2. Metacognitive Monitoring and Control: Cognitive and Neurocognitive Mechanisms

Metacognition has attracted sustained attention from the scientific community over the past decades, particularly within cognitive neuroscience and neuroimaging research. A growing body of studies has sought to identify the neural systems supporting metacognitive monitoring and control. Metacognition operates in conjunction with a wide range of cognitive functions, including memory, reading comprehension, performance monitoring, error detection, and creativity [124, 145, 166]. Conceptually, metacognition is defined as knowledge about and regulation of one’s own cognitive processes [43, 192]. However, it remains a complex and somewhat “fuzzy” construct due to the difficulty of isolating the underlying mechanisms that support reflective evaluation and control of cognition [1, 142].

Understanding metacognition therefore requires examining it in relation to broader neurocognitive processes such as uncertainty monitoring, decision making, and cognitive control. In particular, computational and neuropsychological approaches highlight the central role of uncertainty estimation in metacognitive judgments [44]. From this perspective, metacognition cannot be understood in isolation but must be studied as part of a network of interacting cognitive processes that dynamically regulate ongoing task performance.

Converging evidence from neuroimaging and brain-stimulation studies suggests that metacognition is implemented through a multi-layer neural architecture in which higher-order evaluative systems monitor the outputs of first-order cognitive processes [146, 202]. In this architecture, prefrontal regions encode signals related to task difficulty,

uncertainty, and conflict, and transmit these signals to higher-order monitoring systems. Core components of this evaluative network include the frontopolar cortex, lateral prefrontal cortex, and midline structures such as the dorsal anterior cingulate cortex (dACC) [68, 123]. These regions play a central role in monitoring performance, evaluating uncertainty, and adjusting cognitive control.

Posterior midline structures also play an important role in metacognitive processing. In particular, the precuneus has been identified as a key neural substrate of metacognition, especially in memory-related tasks. Morphological and functional neuroimaging studies, including transcranial magnetic stimulation experiments, indicate that the precuneus acts as a mediator of episodic memory retrieval and its metacognitive evaluation [160]. Functional magnetic resonance imaging studies further demonstrate that regions associated with the default mode network—including the posterior cingulate cortex, precuneus, and superior frontal gyrus—are activated during self-evaluative processes such as monitoring temporal errors [12,150].

Research on reading and language processing provides additional evidence linking executive control systems to metacognitive functioning [87]. Electrophysiological and functional neuroimaging studies of word recognition and reading comprehension show that executive control abilities play a crucial role in monitoring and regulating cognitive performance during complex tasks [14]. These executive processes continue to develop into early adulthood, paralleling structural and functional maturation of prefrontal cortical regions responsible for cognitive control [108].

Despite the progress made in identifying neural substrates of metacognition, an important theoretical question remains unresolved: whether metacognitive processes are domain-general mechanisms applied across cognitive domains, or whether they are domain-specific and tailored to particular types of cognitive activity. This issue remains a central topic of debate in the field [103]. Neuroimaging studies suggest a partially integrated architecture. A distributed network across frontal and posterior midline regions carries signals related to monitoring accuracy and decision validity, whereas multivoxel activity patterns within the anterior prefrontal cortex appear to encode confidence judgments in a domain-specific manner [103]. These findings indicate that metacognitive

monitoring may rely on a hybrid architecture combining domain-general monitoring mechanisms with domain-specific representational processes.

Evidence supporting this view comes from neuroimaging studies examining metacognitive evaluation of mental effort. During metacognitive tasks involving self-assessment of cognitive effort, consistent activation has been observed in the bilateral middle frontal gyri, the left inferior frontal gyrus, the right insula, and the bilateral cingulate cortex [76]. These regions correspond to neural systems involved in cognitive control, interoceptive awareness, and performance monitoring, suggesting that subjective effort evaluation emerges from interactions between these systems [19].

Research involving clinical populations provides additional insights into the neural basis of metacognition [203]. Individuals with neurological impairments or traumatic brain injuries offer valuable opportunities for examining how metacognitive systems operate under altered neural conditions. By comparing patients with healthy control groups, researchers can identify neural systems necessary for effective metacognitive monitoring.

Metamemory research provides a useful framework for examining metacognitive judgments in this context. Two major components of metamemory are learning judgments and retrospective confidence judgments [89]. Learning judgments involve predictions about future memory performance before a task is performed, whereas retrospective judgments involve evaluations of performance after task completion [148]. Neuroimaging studies indicate that these two types of judgments rely on overlapping but partially distinct neural systems.

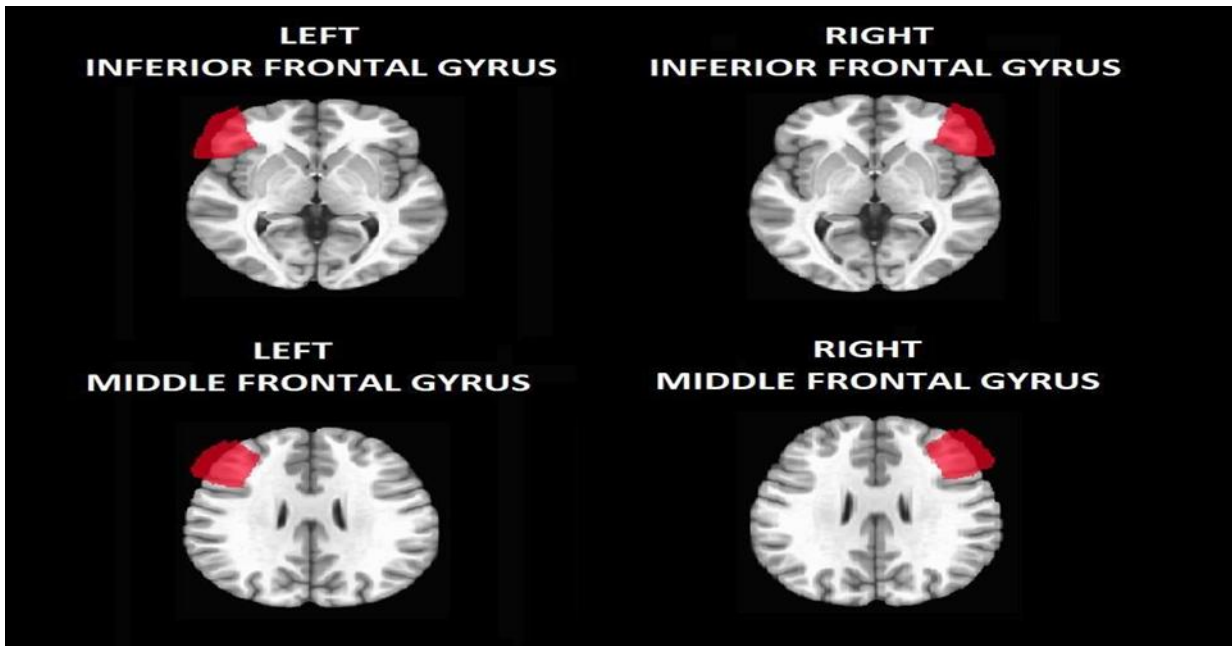
For example, a functional magnetic resonance imaging study examining perceptual decision-making found that positive feedback during perceptual judgments was associated with increased activation in brain regions previously implicated in attention and performance monitoring [163]. Importantly, both retrospective confidence and perceptual accuracy were positively associated with changes in prospective confidence judgments [163], highlighting the dynamic interaction between monitoring processes and performance outcomes.

Further evidence comes from neuroimaging studies involving individuals with traumatic brain injury. In one such study, participants performed a metacognitive task while undergoing fMRI scanning [30]. When patients with traumatic brain injury made retrospective confidence judgments, significant activation was observed in the left supramarginal gyrus, left posterior cingulate cortex, and left cerebellum relative to target recognition tasks. In contrast, healthy control participants showed activation in the left precuneus and bilateral superior temporal gyrus during the same task [30]. When performing retrospective confidence judgments, individuals with traumatic brain injury exhibited greater activity in the contralateral lateral occipital cortex and left cerebellum, whereas healthy controls showed stronger activation in the left supramarginal gyrus [30].

Notably, the two groups differed substantially in the activation of the posterior cingulate cortex and precuneus—regions previously associated with self-referential cognition and conscious evaluation. The absence of a common activation network between groups suggests that individuals with traumatic brain injury may recruit alternative neural substrates to support metacognitive monitoring following injury [30].

A related fMRI study involving participants with traumatic brain injury further examined neural correlates of learning judgments and retrospective confidence judgments [148]. Learning judgments were associated with activation in the left frontal gyrus, bilateral anterior cingulate cortex, mid-insula, and right putamen, whereas retrospective confidence judgments engaged bilateral frontal gyri, anterior and posterior cingulate cortex, the left insula, right putamen, and the left thalamus [62, 148]. In addition, retrospective confidence judgments produced stronger activation in bilateral middle frontal gyri, the left superior frontal gyrus, and bilateral anterior cingulate cortex compared to learning judgments [148]. These findings indicate that metacognitive evaluation involves a distributed network encompassing prefrontal, cingulate, insular, and subcortical regions. Figure 1 depicts several brain regions associated with metacognitive judgments.

Figure 1. Anatomical localization of the bilateral inferior and middle frontal gyri, brain regions associated with metacognitive judgments in neuroimaging studies.



Note: The illustration was generated using AFNI Atlas Daemon.

Metacognition is most commonly assessed through retrospective confidence judgments, as illustrated in many of the studies discussed above. In the present study, however, metacognition is operationalized through participants' subjective ratings of mental effort during mathematical problem solving tasks of varying complexity. Accordingly, it is important to consider the neural systems associated with the perception and regulation of cognitive effort.

Mental effort represents a key component of cognitive control and plays a crucial role in the regulation of cognitive performance. Prolonged cognitive strain is a major contributor to mental fatigue and can significantly reduce the efficiency of cognitive processing [15]. The development of metacognitive skills is closely linked to effort regulation, as metacognitive monitoring guides the allocation of cognitive resources during demanding tasks [200]. In this context, cognitive processes such as working memory and attentional control play a particularly important role in supporting higher-order cognitive functions [38].

Empirical research confirms the relationship between perceived mental effort and metacognitive understanding. In a large experimental study ($N = 156$) investigating learning materials of varying complexity, meta-understanding was found to be strongly associated with perceived mental load and effort, both directly and indirectly through

comprehension processes [125]. These findings suggest that metacognitive monitoring of effort is closely tied to cognitive performance during complex learning tasks.

Neuroimaging studies provide additional evidence linking mental effort to activity within executive control networks. For example, an fMRI study examining cognitive effort across tasks of varying complexity observed sustained activation within the prefrontal cortex, particularly during high-complexity trials [90]. Similarly, wearable electroencephalography studies measuring spectral power changes associated with cognitive effort have demonstrated consistent relationships between electrophysiological markers of effort and metacognitive performance reports [15].

In another fMRI study, participants were asked to perform multiplication tasks of varying difficulty levels. Increasing task complexity was associated with increased activation in a frontoparietal network including the bilateral intraparietal sulcus, left precentral gyrus, right dorsolateral prefrontal cortex, and left pre-supplementary motor area [81]. These results indicate that cognitive effort during mathematical processing recruits neural systems associated with both numerical computation and executive control.

The anterior cingulate cortex and anterior insula, key components of the salience network, are consistently implicated in the experience and regulation of mental effort [6]. This network plays a critical role in detecting behaviorally relevant stimuli and allocating cognitive resources accordingly [72]. However, the salience network has limited capacity, and sustained activation during demanding tasks may contribute to mental fatigue and reduced cognitive efficiency [6].

Consistent with this interpretation, neuroimaging studies examining self-assessment of mental effort during mathematical problem solving have observed increased activation in the bilateral middle frontal gyri, right insula, left inferior frontal gyrus, bilateral precuneus, and left posterior cingulate cortex as task difficulty increases [75, 77]. These regions correspond to core components of metacognitive monitoring and cognitive control networks, suggesting that subjective effort evaluation is tightly coupled with neural systems responsible for monitoring task demands.

Functional neuroimaging studies further indicate that the dorsal anterior cingulate cortex plays a central role in encoding decision uncertainty during metacognitive tasks. Activity within the dACC reflects currently experienced uncertainty during self-monitoring and distinguishes it from uncertainty attributed to others during mentalizing tasks [68]. This suggests that effort-related uncertainty signals are intrinsic to metacognitive monitoring processes. The dACC, together with dorsomedial prefrontal cortex, therefore emerges as a key hub integrating monitoring signals with computations related to cognitive effort allocation.

Additional evidence highlights the role of lateral prefrontal and frontopolar regions in explicit metacognitive evaluation. Both prospective and retrospective metacognitive judgments depend on activity within anterior and lateral prefrontal cortex, supplementary motor area and posterior midline structures such as the precuneus [105, 123]. Brain stimulation studies further support this view: high-intensity transcranial alternating current stimulation applied over the frontopolar cortex selectively disrupts metacognitive accuracy and reduces functional coupling with dorsolateral prefrontal cortex under conditions of high task difficulty [68]. These findings support hierarchical models of metacognition in which frontopolar cortex evaluates signals generated by first-order cognitive processes represented in lateral prefrontal cortex.

The insula also plays a crucial role in linking cognitive effort and metacognitive monitoring. Traditionally associated with gustatory processing, the insula is now recognized as a central region for interoceptive processing—the perception of internal bodily states [51]. Structurally, the insula consists of multiple subdivisions with distinct functional connectivity patterns [143]. The anterior insula forms part of the salience network together with the anterior cingulate cortex and is involved in detecting behaviorally relevant stimuli and coordinating responses across large-scale brain networks [143,159]. The posterior insula, in contrast, is associated with sensorimotor integration and interoceptive sensory processing [29, 39].

Importantly, activity within the anterior insula has been shown to track fluctuations in cognitive control demand and predict adjustments in cognitive strategies [67]. This region interacts dynamically with the default mode network and other large-scale brain

systems involved in cognitive control and self-referential processing [21]. Such interactions suggest that the insula plays a key role in translating internal signals related to effort and uncertainty into adaptive control adjustments. The anterior insula was also found to be involved with autonomic functions [122, 139].

Parietal regions also contribute to the neural architecture linking effort and metacognition. Areas within the inferior and intraparietal cortex are involved in evidence accumulation and representation of task difficulty, providing signals that contribute to confidence judgments and metacognitive evaluation [144, 116]. The right inferior parietal lobe, in particular, encodes external cues related to task difficulty, whereas internal uncertainty signals are distributed across precuneus, lateral frontopolar cortex, and dorsomedial prefrontal cortex [68]. These findings suggest that parietal systems provide important informational inputs that support higher-order metacognitive monitoring processes.

Taken together, the literature reviewed in this section indicates that metacognitive monitoring and mental effort are supported by a distributed neural architecture encompassing prefrontal, cingulate, insular, and parietal regions. These systems operate in concert to evaluate task difficulty, monitor performance, and regulate the allocation of cognitive resources during demanding cognitive tasks. In the following section, the neural mechanisms underlying mathematical cognition will be examined in detail, providing a foundation for investigating how metacognitive monitoring interacts with numerical and arithmetic processing systems.

1.3. Mathematical Cognition: Functional Organization and Cognitive Mechanisms

The concept of mathematical cognition existed long before metacognition, since it dates back to the Sumerian civilization [36]. The Sumerians (4th Millenia BC) used geometry to predict the patterns of planetary motion, a practice that was later adopted and assimilated by many cultures in the Near East [3]. However, it was not until the advent of the Hellenistic era that mathematical knowledge was used by the Pythagoreans (4th

Century BC) in an attempt to create a model of the universe that explained not only the motion of the planets, but also the vast experience of all mankind [25, 115].

Having put a lot of effort into mathematics, the Pythagoreans were the first to create this science [58]. They studied it and came to the conclusion that its fundamental ideas are at the heart of everything. Naturally, numbers come first among these ideas, and since numbers are finite entities in the physical cosmos, everything else is modeled after them in its entirety. Pythagoreans believed that everything is made up of the elements of numbers, and harmony and numbers make up the entire universe [58]. Descartes, a well-known rationalist of the 17th century AC, thought that the only trustworthy source of information was reason. He used mathematics as an example, asserting that innate knowledge is the reason why people can comprehend abstract mathematical ideas without necessarily having any prior experience with them [57]. A great deal of the algebraic notation we use today was not established until Descartes's *Geometria* in 1637 and presently we utilize Leibniz's brilliant notation of calculus, which was developed by Newton and Leibniz fifty years after they systematized calculus [7]

One cognitive ability perhaps exclusive to humans is the ability to work with logical-mathematical symbols, which includes skills such as reasoning, programming, and computation [84]. Mathematical cognition is critical for survival, and the modern mind has unique abilities due to the gradual development of mathematical thinking [96].

Quality of life, well-being, and future employment are correlated with metacognition as well as numerical skills [53, 78, 92]. One study provided empirical data indicating that the capacity to carry out fundamental mathematical computations is inversely related to the likelihood of defaulting on a mortgage [52]. Global studies indicate that a significant number of individuals struggle with fundamental numerical abilities, which are crucial for managing their health and making educated medical choices [42, 120]. Poor numeracy decreases adherence to medication, hinders access to therapies, complicates risk communication [thus restricting prevention initiatives for the most at-risk populations], and seems to negatively influence medical outcomes [120]. Mathematical concepts are not separate from each other; rather, they are built into a dynamic system of mathematical cognition [53]. The formation of each mathematical concept, as well as the connections

between them, is influenced by common cognitive abilities and different learning situations [53]. Mathematics, which is a fundamental subject, has an important applications in education, and the improvement of educational procedures, require an understanding of the cognitive processes underlying mathematical cognition, however, understanding and practice in this discipline are severely hampered by anxiety and cognitive impairments related to mathematics [149, 162, 201].

Contemporary theories posit that human mathematical cognition builds on an evolutionarily older “number sense” for approximate quantity, implemented as an analog magnitude code that supports non-symbolic numerosity judgments [e.g., dot arrays]. This approximate number system (ANS) is thought to provide a neurobiological platform that is progressively linked to symbolic systems [digits, number words] during development [56, 133].

At the level of arithmetic and algebra, meta-analytic and single-study work converges on a distinction between magnitude-based calculation and transformation, which rely more heavily on quantity representations; and fact retrieval and rule-based operations, which draw on verbal/semantic systems and long-term memory [134]. More abstract mathematics [e.g., higher-level algebra, topology] appears to “recycle” circuits originally engaged in elementary number sense: professional mathematicians engage bilateral intraparietal and ventral temporal regions rather than perisylvian language or generic temporal semantic networks when reflecting on advanced mathematical concepts, even for verbalized mathematical facts [5]. This supports the view that mathematical semantics form a specialized subsystem within broader semantic architectures

According to the triple code model in mathematical cognition, different substrates of the brain encode the processing of visual, auditory, and non-symbolic numerical information [133].

The Triple Code Model proposes three partially dissociable codes for number:

1. Analog magnitude code for nonsymbolic quantities.
2. Visual–Arabic code for written numerals.
3. Verbal code for number words and arithmetic facts.

fMRI evidence supports this functional differentiation but also emphasizes a distributed and overlapping fronto–parietal network that is recruited across all codes, suggesting that attention and working memory are tightly integrated with numerical representations [133].

Various cognitive functions such as attention, memory, and spatial orientation are associated with the efficiency of solving mathematical problems [107, 113, 156]. Information processing efficiency has been found to be a factor that affects mathematical performance (response time and accuracy in solving math tasks) in students aged 8 to 11 years [111]. Computational, automatic, and memory recovery skills are considered prerequisites for the development of mathematical cognition [69]. Working memory works in several parietal and frontal regions of the brain (specifically the intraparietal sulcus, supramarginal gyrus, and ventral and dorsal aspects of the lateral prefrontal cortex), which are also associated with mathematical cognition [97].

Mathematical cognition is strongly constrained by domain-general resources. Working memory and executive control support multi-step calculation, algebraic manipulation, and problem solving. Cognitive control and strategy selection determine whether problems are solved procedurally or via retrieval, with corresponding neural specializations [9]. Affect and motivation (e.g., mathematics anxiety) modulate engagement with mathematical tasks and can interact with metacognitive monitoring and control processes, especially under pressure, for instance in word-problem solving or learning contexts [137, 151, 157, 164]. These factors are increasingly modeled in multi-component theories that separate first-order numerical representations from higher-order control, monitoring, and affective systems [193].

A meta-analysis, which included arithmetic tests in both symbolic and non-symbolic formats, based on 28 neuroimaging studies, 12 transcranial magnetic stimulations, and 12 studies of brain-damaged patients, showed that both intraparietal sulci were activated in all tasks; however, the results of studies in people with brain damage differed from those of neuroimaging studies, indicating right hemisphere lateralization for non-symbolic formats [40].

Because the ventral temporal cortex contains math-selective hubs, it has been demonstrated that specific brain regions code for symbolic numerical representations when visualizing numbers and performing arithmetic operations [32, 41]. Bilateral ventral temporal areas implicated in elementary number sense are recycled during mathematical reflection, according to fMRI studies [5]. Visuospatial cognition is directly related to mathematical cognition through the visual processing of numerals [24]. In a study, temporal cortex sites displayed an initial burst of high-frequency broadband activity that diminished as the operands grew larger but had a constant integral throughout the whole trial. It was speculated that, beyond just digit recognition, the temporal cortex may play a part in early problem difficulty identification [32]. The aim of another study was to summarize the information on the brain basis of mathematical cognition in healthy individuals offered by various transcranial magnetic stimulation procedures [49]. There were 21 experimental trials involving people who received transcranial magnetic stimulation in various forms, including theta burst stimulation, repeated transcranial magnetic stimulation, and transcranial magnetic stimulation with one impulse [49]. When transcranial magnetic stimulation was administered to specific parietal and prefrontal regions of the brain, it evoked neuromodulatory effects that can be measured in behavior and that have an impact on cognitive processes related to number processing, arithmetic, and quantities [49].

A central behavioral regularity in basic arithmetic is that performance worsens as problem size increases: larger operands yield longer response times and higher error rates. In timed multiplication verification, for example, reaction time increases with problem size and also depends on how close an incorrect answer is to the correct one (a “split”/distance-like effect), indicating that difficulty is not just about computing but also about decision processes during verification [2].

Importantly, “problem size” is partly a learning-history variable: elementary curricula exhibit a strong small-fact frequency bias [small facts appear far more often than large facts], which plausibly contributes to greater fluency (and thus lower apparent difficulty) for small problems [8] This matters because any operand-size manipulation conflates computational complexity with differential practice.

Beyond item characteristics, difficulty can be conceptualized as the amount of control/attention required to maintain task goals, suppress competitors, and select a response. Evidence from large-scale individual-differences work in children shows that arithmetic performance covaries with processing speed, working memory, and language-related measures, consistent with a domain-general resource component in arithmetic fluency—especially when tasks are less automatized [48, 61]. Complementarily, executive attention appears as a broad predictor across arithmetic formats and demands, supporting the idea that “difficulty” often reflects coordination costs rather than only numerical magnitude computations [121].

Operation differences are rarely explained by a single “difficulty” axis; they often reflect differences in the mixture of strategies (direct retrieval vs. procedural computation) that participants deploy [41]. Developmental evidence shows that children follow distinct trajectories in their use of cognitive vs. manipulative/procedural strategies, and these trajectories relate to later mathematics achievement—implying that what counts as “hard” depends on which strategy is available and chosen [27].

Neurophysiological evidence in children further supports this strategy account: retrieval vs. procedural solving is associated with dissociable oscillatory signatures (e.g., relatively stronger left-hemispheric theta synchronization for retrieval and stronger alpha desynchronization for procedures), and—crucially—operation differences can remain even within retrieval trials, suggesting that “retrieving multiplication” is not necessarily identical to “retrieving subtraction/addition” in processing demands or representational content [23].

Operation contrasts are theoretically informative because they can shift reliance between magnitude-oriented and fact-retrieval systems. fMRI evidence indicates that multiplication (as a prototypical fact-retrieval operation) can engage the left angular gyrus more than subtraction, whereas subtraction shows comparatively stronger intraparietal sulcus involvement (classically associated with magnitude processing), at least in some samples/conditions [117]. Network-level modeling similarly suggests that operations can differ in effective connectivity patterns and in the auxiliary engagement of phonological/visual/motor processes, implying that “difficulty” may be instantiated as

different computational bottlenecks across operations rather than a unitary load scalar [158].

Language skills can constrain arithmetic development through mapping and accessing symbolic codes (e.g., learning labels for numerals and translating between formats), which in turn affects how readily problems can be solved by retrieval rather than procedure [54, 118]. At the individual-differences level, shared variance between reading and arithmetic fluency is strongly tied to serial retrieval fluency—consistent with the idea that fluent access to ordered verbal/symbolic sequences supports rapid fact retrieval [73]. These links predict especially strong operation differences when an operation is more retrieval- and lexicon-dependent (often multiplication) rather than procedure-friendly.

Researchers have found that the relationship between inhibitor control and mathematics is sometimes "weaker than expected," despite the fact that people explicitly use inhibitory control in mathematical settings, and they will soon be able to fully explore the mechanical role of the cognitive processes involved in math problems, taking into account the context (e.g., participant state, previous knowledge) [93]. The increasing involvement of context suggests new perspectives on executive functions, and these perspectives have implications for mathematical cognition research [93].

In a recent study brain responses of two groups of students were monitored, one with high fractional competence and the other with low fractional competence when they solved simple and complex fractional problems [47]. In the high competence group, fraction complexity resulted in greater activation in the right dorsomedial frontal region, but not in the low competence group [47]. Based on their higher behavioral scores, these findings imply that only the highly competent group used frontal cognitive resources [47]. In another study, participants were divided into three groups (low, medium, and high) according to their cognitive scores, and it was found that when performing math tasks using creative mathematical thinking as opposed to algorithmic thinking, participants performed better and showed increased activity in critical brain regions associated with mathematical cognition, including the left lower/middle frontal gyrus and left angular gyrus [153]. Although the moderate and high cognitive ability groups had an impact on performance, no interaction was observed between the effects of creative mathematical

thinking and cognitive ability [153]. Regardless of cognitive ability, encouraging learners to engage in positive processes while learning mathematical reasoning leads to the long-term impact of learning on brain activation [153].

fMRI research on developmental dyscalculia illustrates both the importance and heterogeneity of neural substrates. Single-case and multivariate approaches comparing dyscalculic and typically developing children performing non-symbolic number comparison and exact calculation tasks reveal:

- Relatively subtle group-level differences in parietal regions (e.g., angular gyrus, parieto-occipital sulcus).

- Pronounced individual differences, often centered on visual processing areas, with some children showing compensatory upregulation of higher visual or fronto-parietal regions.

- The possibility to distinguish most dyscalculic from typically developing children using multivariate activation patterns across fronto-parietal systems, suggesting that deficits in visual-parietal number representation may be compensated by finger- or strategy-related fronto-parietal processes [37].

Such findings underscore that the mathematical network is not fixed but can be reorganized, with implications for targeted interventions and for understanding the neural basis of mathematical learning difficulties.

While studying gender differences and similarities in mathematical cognition, the brain responses of 24 men and 25 women were compared during a math task that involved addition and subtraction of three operands [70]. There were marked gender differences in functional brain activation in the right dorsal and ventral visuospatial processing streams, despite no differences in accuracy or response time between males and females [70]. In men, there was higher activation of ventral flow in the right lingual and parahippocampal gyrus, as well as greater activation of dorsal flow in areas of the angular gyrus of the standard mode network (which are typically deactivated during complex cognitive tasks) and in the right intraparietal sulcus, which are critical for mathematical cognition [70].

1.4. The Interaction Between Metacognitive Monitoring and Mathematical Cognition: Theoretical Models and Neurocognitive Evidence

The theoretical and empirical literature reviewed in the preceding sections demonstrates that metacognition and mathematical cognition have traditionally been investigated within largely separate research traditions. Studies of mathematical cognition have primarily focused on neural systems supporting numerical representation, symbolic processing, and arithmetic operations, most notably within the fronto-parietal network that includes the intraparietal sulcus, inferior frontal gyrus, and temporo-parietal regions [32, 86, 135]. In contrast, research on metacognition has concentrated on neural systems responsible for monitoring uncertainty, evaluating performance, and regulating cognitive control, typically associated with medial and lateral prefrontal cortex, the dorsal anterior cingulate cortex, anterior insula, and posterior midline structures such as the precuneus [108, 119].

Despite the significant progress achieved in both areas, relatively little attention has been paid to the mechanisms through which metacognitive monitoring interacts with domain-specific cognitive processes such as mathematical reasoning. In particular, the role of subjective mental effort as a metacognitive signal during mathematical problem solving remains insufficiently understood at the neural level. Existing studies often examine metacognitive monitoring in perceptual or memory tasks, while research on mathematical cognition typically focuses on computational mechanisms underlying arithmetic and numerical representation. As a result, the integration between metacognitive regulation and mathematical processing remains theoretically underdeveloped.

A productive conceptual framework for integrating these domains is provided by hierarchical models of metacognition, most prominently the model proposed by Nelson (1990), which distinguishes between two interacting levels of cognitive organization: the object level and the meta-level. The object level corresponds to the execution of cognitive operations required for task performance, whereas the meta-level monitors and regulates these operations through evaluative and control processes. Information flows between the two levels through monitoring and control loops: the meta-level evaluates the state of object-level processing and adjusts cognitive control accordingly.

Building on this theoretical foundation, the present dissertation proposes an integrative neurocognitive model that conceptualizes the relationship between mathematical cognition and metacognitive monitoring as a two-level functional architecture.

At the object level, mathematical cognition is implemented through neural systems responsible for numerical representation, symbolic manipulation, and computational procedures. These processes rely primarily on the fronto-parietal network associated with numerical cognition, including the intraparietal sulcus, inferior frontal gyrus, ventral temporal regions involved in symbolic number recognition, and other regions supporting working memory and executive processing during arithmetic problem solving [32, 86, 135]. Within this system, different arithmetic operations and levels of task complexity recruit partially overlapping but functionally specialized neural circuits supporting magnitude processing, fact retrieval, and procedural computation.

At the meta-level, metacognitive monitoring and control processes evaluate ongoing cognitive activity and regulate the allocation of cognitive resources. These functions are supported by a domain-general control network involving the dorsal anterior cingulate cortex, anterior insula, and lateral prefrontal cortex [82, 102, 139]. These regions have been consistently implicated in performance monitoring, detection of conflict or uncertainty, estimation of task difficulty, and the regulation of cognitive effort.

Within this framework, subjective mental effort represents a key metacognitive signal linking the meta-level and the object level. During mathematical problem solving, increasing task difficulty and cognitive demand generate signals related to uncertainty, conflict, and processing cost. These signals are monitored by the metacognitive system, which evaluates whether additional cognitive resources should be allocated to maintain task performance. As a result, perceived effort can be understood as both the outcome of metacognitive monitoring and a regulatory variable that influences subsequent cognitive control processes.

Importantly, the interaction between these levels forms a closed-loop regulatory system. Monitoring signals originating at the meta-level influence the allocation of attention, working memory, and executive control during object-level mathematical

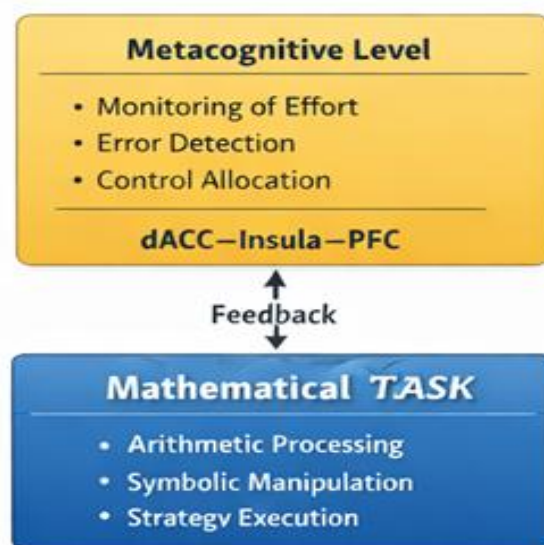
processing. In turn, the results of mathematical computations provide feedback to the metacognitive system, updating estimates of task difficulty, confidence, and subjective effort. This dynamic interaction allows individuals to adaptively regulate their cognitive resources during complex mathematical activity [197].

The proposed model therefore suggests that mathematical cognition cannot be understood solely as a domain-specific computational system. Instead, it should be viewed as an integrated cognitive architecture in which domain-specific numerical processing systems interact continuously with domain-general metacognitive monitoring and control mechanisms.

From a neurocognitive perspective, this framework predicts the existence of partially overlapping yet functionally differentiated neural systems supporting mathematical computation and metacognitive monitoring. Mathematical tasks are expected to engage both domain-specific numerical regions and domain-general control networks, whereas metacognitive evaluation of mental effort primarily recruits monitoring and control systems. At the same time, the degree of activation within these networks should be modulated by task difficulty and computational demand.

The conceptual structure of the proposed two-level architecture of mathematical cognition and metacognitive monitoring is illustrated in Figure 2.

Figure 2. Conceptual Model of Metacognition in Mathematical Cognition



The integrative model developed in this section provides the theoretical basis for the empirical investigation presented in the following chapter. Specifically, it allows the formulation of testable hypotheses regarding the neural overlap and dissociation between mathematical problem solving and metacognitive evaluation of mental effort, the modulation of neural activation by task complexity, and the functional organization of domain-general and domain-specific cognitive systems.

KEY CONCLUSIONS FOR CHAPTER 1

1. The analysis of contemporary theoretical and empirical literature demonstrates that metacognition and mathematical cognition should be regarded as interrelated components of cognitive activity which, despite having often been studied separately, form a functionally connected system within the structure of intellectual performance. Metacognitive processes provide monitoring, evaluation, and regulation of activity, whereas mathematical cognition is realized through the processing of symbolic and quantitative information in the course of problem solving. This conclusion substantiates the relevance of examining these processes within a unified psychological framework.

2. Theoretical approaches to metacognition indicate that subjective mental effort may be interpreted as a significant metacognitive indicator reflecting the perceived difficulty of a task, the current state of cognitive resources, and the degree of control required for successful performance. Mental effort should therefore be understood not only as a subjective correlate of task demands, but also as a regulatory signal involved in the organization of cognitive activity. This conclusion is consistent with the theoretical position advanced in the dissertation concerning the regulatory role of subjective mental effort.

3. The literature on mathematical cognition shows that mathematical thinking constitutes a complex form of cognitive activity that depends both on domain-specific mechanisms of quantitative and symbolic information processing and on domain-general mechanisms of working memory, executive control, and strategic regulation. This provides a basis for considering mathematical cognition as a hierarchically organized system that includes both task-related operations and higher-order regulatory processes.

4. The synthesis of research on metacognition, mental effort, and mathematical cognition makes it possible to substantiate a two-level model of cognitive activity, according to which mathematical problem solving may be interpreted as the object-level of processing, whereas metacognitive monitoring constitutes the meta-level responsible for the evaluation of task difficulty, subjective effort, and the regulation of performance.

This model provides the theoretical foundation for the general hypothesis of the study and for the provisions submitted for defense.

5. Neurocognitive studies reviewed in the chapter indicate that metacognitive monitoring and mathematical cognition rely on partially overlapping, yet functionally differentiated, systems. Metacognitive monitoring is primarily associated with mechanisms of cognitive control, uncertainty evaluation, and self-regulation, whereas mathematical cognition additionally involves specialized systems supporting numerical representation and arithmetic processing. These data support the assumption of both integration and differentiation between the processes under investigation.

6. The review of the literature reveals an important theoretical and empirical gap: despite substantial progress in the study of metacognition and mathematical cognition, the interaction between metacognitive monitoring of mental effort and mathematical problem solving has not been sufficiently investigated within a unified experimental paradigm. In particular, insufficient attention has been paid to the relationship between subjective mental effort, objective task difficulty, and the functional organization of mathematical processing. This gap determines the logic of the empirical part of the dissertation.

7. Thus, the first chapter provides the theoretical and methodological foundation for the empirical study by substantiating the view that metacognitive monitoring is an immanent component of mathematical cognition, clarifying the role of subjective mental effort as a mechanism of cognitive regulation, and justifying the need for an integrative investigation of these processes within the framework of contemporary cognitive psychology.

CHAPTER 2. EMPIRICAL STUDY OF INTERACTION BETWEEN METACOGNITIVE MONITORING AND MATHEMATICAL COGNITION

2.1. Objectives and Theoretical Basis of the Empirical Study

The empirical part of the dissertation was designed to investigate the interaction between metacognitive monitoring of subjective mental effort and mathematical cognition, and to identify the functional mechanisms underlying this interaction using neuroimaging methods. In accordance with the general logic of the study, the empirical investigation was aimed not merely at describing neural activation associated with arithmetic performance and metacognitive evaluation, but at clarifying the role of metacognitive monitoring in the regulation of mathematical thinking as a form of complex cognitive activity. This approach corresponds to the general objective of the dissertation, namely, to identify and empirically substantiate the nature of the interaction between metacognitive processes of monitoring and control and the processes underlying mathematical thinking, as well as to determine their functional organization.

The need for such an empirical investigation follows from the theoretical analysis presented in Chapter 1. That analysis showed that metacognition and mathematical cognition have most often been examined within relatively independent research traditions. Metacognitive monitoring has primarily been studied in relation to perception, memory, and decision-making, whereas mathematical cognition has mainly been investigated in connection with numerical representation, symbolic processing, and arithmetic operations. As a consequence, the interaction between metacognitive monitoring and mathematical cognition has remained insufficiently explored, particularly within a unified experimental design allowing direct comparison between mathematical processing and subsequent metacognitive evaluation.

The theoretical framework of the empirical study is based on the assumption that mathematical cognition and metacognitive monitoring constitute interrelated yet functionally distinct levels of cognitive organization. Within this framework, mathematical problem solving is understood as the object-level of cognitive activity, at

which symbolic and quantitative information is processed in the course of performing arithmetic operations. Metacognitive monitoring, by contrast, is conceptualized as the meta-level of regulation, responsible for evaluating task demands, monitoring the adequacy of ongoing performance, assessing subjective mental effort, and supporting the allocation of cognitive resources. Thus, metacognitive monitoring is regarded not as an external accompaniment to mathematical thinking, but as an immanent component of its functional organization.

A central place in this model is occupied by the construct of subjective mental effort. In the present study, subjective mental effort is treated as a metacognitive indicator reflecting the perceived difficulty of task performance and the current state of cognitive load. At the same time, it is viewed as a regulatory signal that participates in the coordination of cognitive resources during problem solving. Such an interpretation is consistent with the theoretical position advanced in the dissertation, according to which subjective effort does not merely accompany performance phenomenologically, but performs an important function in the organization and regulation of cognitive activity. This understanding also provides the basis for the operationalization of metacognitive monitoring in the empirical part of the study.

The empirical study was therefore constructed around several interrelated theoretical assumptions.

First, it was assumed that metacognitive monitoring of mental effort and mathematical cognition represent two interconnected but functionally distinguishable levels of cognitive activity. From this perspective, successful mathematical performance depends not only on the implementation of arithmetic operations as such, but also on metacognitive processes that monitor task difficulty, evaluate the adequacy of performance, and regulate the expenditure of mental effort. This assumption corresponds to the general hypothesis of the dissertation and serves as the conceptual basis for the empirical design.

Second, it was assumed that metacognitive monitoring and mathematical cognition rely on partially overlapping mechanisms of cognitive control. In particular, the subjective evaluation of mental effort and the solution of arithmetic problems were

expected to engage common functional systems involved in monitoring uncertainty, detecting cognitive conflict, and regulating performance. At the same time, this overlap was not expected to eliminate the distinction between the processes under investigation, since metacognitive evaluation and mathematical processing were presumed to serve different roles within the overall organization of activity.

Third, mathematical cognition was assumed to involve domain-specific mechanisms in addition to domain-general control processes. The solution of arithmetic problems was expected to depend on specialized systems supporting the processing of quantitative and symbolic information, thereby distinguishing mathematical cognition from more general forms of metacognitive monitoring. This assumption follows directly from the theoretical synthesis presented in Chapter 1 and is important for substantiating the proposition that mathematical thinking possesses a specific functional organization while at the same time remaining embedded in a broader regulatory architecture.

Fourth, it was assumed that increases in the objective difficulty of mathematical tasks would lead to greater engagement of metacognitive monitoring mechanisms and to higher subjective ratings of mental effort. This assumption reflects the view that metacognitive monitoring is dynamically involved in the regulation of cognitive activity and becomes increasingly important under conditions of heightened task demands. Thus, the empirical study was intended not only to identify the existence of shared and distinct mechanisms, but also to examine how the interaction between mathematical processing and metacognitive monitoring changes as a function of task complexity.

Fifth, it was assumed that different arithmetic operations would be associated with different cognitive strategies and, accordingly, with distinct functional profiles within the broader system of mathematical cognition. Addition, subtraction, multiplication, and division were therefore treated not simply as different task categories, but as different modes of mathematical processing that place different demands on both computational and regulatory mechanisms. This assumption is important for clarifying the internal differentiation of mathematical cognition and for demonstrating that arithmetic activity cannot be reduced to a single homogeneous mechanism.

Sixth, the study proceeded from the assumption that mathematical cognition and metacognitive monitoring differ in their hemispheric organization. Mathematical processing was expected to display more pronounced left-hemispheric specialization, whereas metacognitive monitoring was presumed to show a more bilateral pattern of functional organization. This assumption was included in the study in order to clarify the broader organization of the processes under investigation and to test whether differences between object-level and meta-level functioning are reflected not only in their roles within cognition but also in their large-scale functional architecture.

In accordance with these assumptions, the empirical study was designed to address the following objectives: to compare the functional correlates of arithmetic problem solving and subsequent metacognitive evaluation of subjective mental effort within a unified experimental paradigm; to determine the degree of overlap and differentiation between the mechanisms involved in mathematical cognition and metacognitive monitoring; to examine the effect of task difficulty on subjective effort and on the engagement of functional systems associated with cognitive control; to identify differences related to the type of arithmetic operation; and to interpret the findings in the context of contemporary theories of metacognition, self-regulation, and mathematical thinking.

Thus, the empirical part of the dissertation is grounded in the view that mathematical cognition should be understood as a hierarchically organized and cognitively regulated form of intellectual activity. Within this framework, metacognitive monitoring of subjective mental effort serves as a key mechanism linking the object-level of mathematical processing with the meta-level of evaluation and control. The use of functional magnetic resonance imaging in the present study made it possible to investigate this interaction at the level of functional organization and thereby to provide empirical support for the integrative model proposed in the dissertation.

2.2. Organization of the Empirical Study and Research Methods

Participants

The empirical sample consisted of 20 healthy young adults, including 10 women and 10 men, with a mean age of 23.85 years. All participants were right-handed, which was verified during the preliminary screening procedure. Behavioral pre-screening was conducted prior to the main experiment in order to ensure compliance with the inclusion criteria and to maintain a relatively homogeneous sample with respect to task performance. Participants were excluded if they were left-handed, failed to complete the number-matching task during screening, or demonstrated extremely high or extremely low performance on the preliminary mathematical task. These criteria were introduced in order to reduce possible ceiling and floor effects and to ensure comparability of the experimental data across participants. All participants provided written informed consent in accordance with accepted ethical standards.

General Organization of the Empirical Study

The empirical study was organized as a task-based functional magnetic resonance imaging experiment designed to examine the interaction between mathematical cognition and metacognitive monitoring of subjective mental effort within a unified experimental paradigm. The design made it possible to compare, within the same participant, the processes involved in solving arithmetic problems of varying complexity and the subsequent metacognitive evaluation of the effort expended during task performance. In this respect, the study was intended to capture both the object-level of mathematical processing and the meta-level of monitoring and regulation.

The experimental paradigm included three principal components: mathematical task performance, metacognitive evaluation, and a baseline fixation period. In addition, a control task was incorporated in order to account for low-level visual-perceptual and decision-related processes not specific to mathematical computation. This design made it possible to isolate the functional correlates of arithmetic processing proper, to examine the neural correlates of metacognitive monitoring of subjective effort, and to compare

shared and functionally specific mechanisms underlying these two components of cognitive activity.

Experimental Design and Procedure

During scanning, participants were presented with arithmetic tasks involving four operation types: addition, subtraction, multiplication, and division. The tasks varied across three levels of objective difficulty, defined by the number of digits in the operands: one-digit, two-digit, and three-digit problems. The manipulation of task difficulty was introduced in order to examine whether increasing computational demands would be accompanied by corresponding changes in metacognitive monitoring and subjective ratings of mental effort. The inclusion of different arithmetic operations made it possible to investigate the internal differentiation of mathematical cognition and to compare distinct cognitive strategies involved in arithmetic processing.

Each experimental block consisted of arithmetic problems belonging to a specific operation type and difficulty level. Across the experiment, participants completed blocks covering all combinations of arithmetic operation and task difficulty. Mathematical trials were accompanied by control trials in which participants were required to compare the fonts of visually presented numbers rather than solve arithmetic problems. The control condition was included to control for visual analysis, motor response selection, and elementary decision-making processes that are not specific to mathematical cognition. In total, 36 mathematical blocks were presented across the experiment. The structure of the experimental paradigm, examples of the mathematical stimuli, and a single run are presented in Table 1-3.

Task difficulty was manipulated across three levels, defined by the number of digits in the operands:

- low difficulty — one-digit numbers
- medium difficulty — two-digit numbers
- high difficulty — three-digit numbers

Table 1: Structure of the experimental paradigm used in the fMRI study investigating the relationship between mathematical cognition and metacognitive monitoring of mental effort.

Phase	Task Type	Description	Number of Trials	Purpose
1	Mathematical Task Block	Participants solved arithmetic problems involving four operations: addition, subtraction, multiplication, and division. Problems were presented with four response options.	12 mathematical trials	To engage mathematical cognition and numerical processing systems
2	Control Trials	Participants compared visual font styles of numbers instead of performing calculations.	3 control trials	To control for visual perception and decision-making processes
3	Metacognitive Evaluation	Participants rated the mental effort experienced during the previous task block using a 4-point scale.	1 rating	To measure subjective metacognitive monitoring of effort
4	Fixation Period	Participants viewed a fixation cross.	10 seconds	Baseline condition and recovery interval before next block

Table 2. The examples of mathematical operations and the metacognition task used in the experiment.

	Light Level	Average Level	High Level
Addition	5+9	32+36	859+213
	13 15 16 14	78 69 67 68	1062 972 1172 1072
Subtraction	9-3	101-54	1563-531
	5 7 4 6	37 57 48 47	832 922 942 932
Multiplication	5x7	28x8	453x8
	42 40 30 35	216 214 324 224	3524 3724 3614 3624
Division	30/5	228/3	2472/4

	8 5 7 6	86 77 75 76	518 718 608 618
Control	5#5	82#82	540#540
	5 5 5 5	82 82 82 82	540 540 540 540
Metacognition task	Please evaluate the effort spent on the previous tasks		
	1 2 3 4		

Table 3: Example of a single run

Block 1	MUL3
Block 2	SUB2
Block 3	DIV1
Block 4	ADD3
Block 5	DIV3
Block 6	MUL1
Block 7	DIV2
Block 8	ADD1
Block 9	CONT3
Block 10	SUB3
Block 11	CONT1
Block 12	MUL2
Block 13	SUB1
Block 14	ADD2
Block 15	CONT2

Following each mathematical block, participants performed a metacognitive evaluation task. In this phase, they were asked to rate the subjective mental effort experienced during the preceding block of arithmetic problems. Ratings were made on a four-point scale corresponding to increasing levels of perceived cognitive effort. In the context of the present study, these ratings were treated as an operational measure of metacognitive monitoring of mental effort. Each evaluation period was followed by a 10-second fixation interval, during which participants viewed a fixation cross. This interval

served as a baseline condition and as a brief recovery period before the onset of the next block. Thus, the overall structure of the experimental cycle was as follows: mathematical problem solving → metacognitive evaluation of effort → fixation. The overall structure of the experimental paradigm is illustrated in Figure 3.

Such an organization of the experiment made it possible to examine, within a single design, several key aspects of the research problem: the functional correlates of mathematical processing, the functional correlates of metacognitive monitoring, the degree of overlap and differentiation between these processes, the influence of objective task difficulty on both mathematical performance and effort evaluation, and the specific features associated with different arithmetic operations. Accordingly, the design directly corresponded to the central aim and hypotheses of the dissertation.

Figure 3. Experimental Design (fMRI Paradigm)



fMRI Data Acquisition

Primary data acquisition was carried out at the National Research Centre “Kurchatov Institute” (Moscow) using a Siemens Magnetom Verio magnetic resonance imaging scanner with a field strength of 3 Tesla. Functional imaging data were acquired using a gradient echo-planar imaging sequence sensitive to blood-oxygen-level-dependent signal changes, producing T2*-weighted functional images suitable for the

analysis of task-related brain activity. Acquisition parameters, including repetition time, echo time, slice thickness, and matrix size, were implemented in accordance with standard protocols for cognitive fMRI studies used at the research site. The selected acquisition settings ensured an appropriate balance between spatial resolution, temporal resolution, and sensitivity to BOLD signal fluctuations associated with the performance of cognitive tasks.

Preprocessing of Neuroimaging Data

Preprocessing of functional and anatomical neuroimaging data was carried out using the AFNI software package. The preprocessing pipeline included standard stages required for the analysis of task-based fMRI data. First, slice timing correction was applied in order to compensate for temporal differences in slice acquisition within each functional volume. Second, head motion correction was performed using rigid-body alignment procedures with estimation of six motion parameters. Third, functional images were coregistered with high-resolution anatomical images for each participant. Fourth, all data were spatially normalized to the standard MNI stereotaxic space, which allowed comparisons at the group level. Fifth, spatial smoothing was applied using a Gaussian kernel with a full width at half maximum of 4 mm in order to increase the signal-to-noise ratio and to compensate for interindividual anatomical variability [55]. Finally, masking procedures were used to remove signals originating from non-brain tissues.

The preprocessing strategy was selected so as to ensure the reliability of subsequent group analyses and to allow valid comparison of the functional correlates of mathematical cognition and metacognitive monitoring across participants and experimental conditions. In methodological terms, these procedures correspond to current standards of functional neuroimaging research and provide a sufficient basis for investigating the organization of complex cognitive processes.

Statistical Analysis

Statistical analysis of the fMRI data was conducted within the framework of the general linear model and included both individual-level and group-level analyses. At the individual level, regression models were estimated for each participant using AFNI tools. The design matrix included regressors corresponding to mathematical task conditions

defined by arithmetic operation and difficulty level, metacognitive evaluation periods, control task blocks, and fixation baseline. In addition, nuisance regressors representing head movement parameters were included in order to reduce the influence of motion-related artifacts.

A series of contrasts of interest was then computed in order to identify functional activity associated with: metacognitive evaluation in comparison with baseline and control conditions; mathematical problem solving in comparison with baseline and control conditions; differences across arithmetic operations; and differences associated with task difficulty. This analytical strategy made it possible to examine both the shared and the functionally specific mechanisms involved in mathematical cognition and metacognitive monitoring, as well as the modulation of these mechanisms by increasing objective task complexity.

At the group level, individual contrast maps were entered into a random-effects analysis. Statistical significance was determined using correction for multiple comparisons in accordance with accepted standards of fMRI data analysis. In addition to whole-brain analysis, a region-of-interest analysis was conducted for statistically significant activation clusters. This made it possible to examine BOLD signal dynamics in key regions associated with mathematical processing and cognitive control, and to clarify their anatomical localization using the atlas tools implemented in AFNI.

Methods of Psychological Interpretation

Although the empirical study employed neuroimaging methods, the interpretation of the obtained data was carried out within the conceptual framework of cognitive psychology. Functional activation patterns were analyzed not as isolated neuroanatomical facts, but as indicators of the organization of cognitive activity, including mathematical processing, metacognitive monitoring, regulation of mental effort, and the coordination of cognitive resources under varying task demands. In this respect, the methodological logic of the empirical study corresponds to the general orientation of the dissertation toward clarifying the role of metacognition in the structure and regulation of mathematical thinking.

Thus, the methods used in the empirical part of the dissertation made it possible to investigate the interaction between metacognitive monitoring and mathematical cognition within a controlled experimental context, to compare their functional organization, and to identify the role of subjective mental effort as a metacognitive indicator of cognitive load and regulation. The selected design and methods therefore provided an adequate basis for testing the hypotheses of the study and for addressing the research objectives formulated in the introduction.

2.3 Results of the Empirical Study

2.3.1. Behavioral Indicators of Mathematical Performance and Subjective Mental Effort

At the first stage of the analysis, the behavioral indicators of task performance were examined in order to characterize the cognitive demands of the experimental conditions and to determine whether the manipulation of arithmetic difficulty and operation type was reflected at the level of observable performance. Particular attention was paid to two classes of behavioral indices: objective parameters of mathematical task performance and subjective ratings of mental effort provided during the metacognitive evaluation phase.

The behavioral data indicate that mathematical performance varied systematically as a function of both task difficulty and arithmetic operation type. As the objective difficulty of the problems increased, participants demonstrated a tendency toward reduced performance efficiency, reflected in lower accuracy and/or greater response demands during arithmetic processing. These changes were accompanied by corresponding increases in subjective ratings of mental effort, indicating that participants were sensitive to the manipulation of task complexity and were able to differentiate between levels of cognitive demand. The main behavioral tendencies observed across conditions are summarized in Table 4, while the general structure of the experimental sequence within which these indicators were obtained is shown in Figure 3 (see above).

The observed relationship between objective task difficulty and subjective effort ratings is of particular importance for the logic of the present study. In psychological terms, this pattern suggests that subjective mental effort may be treated as a valid

metacognitive indicator of the current demands imposed on cognitive activity. The fact that participants' self-reports varied in accordance with the experimental manipulation supports the assumption that effort ratings reflected not arbitrary introspective judgments, but a meaningful monitoring process sensitive to differences in the complexity of arithmetic performance.

Behavioral differences were also found across arithmetic operations. Although all operation types required symbolic and quantitative processing, they differed in the degree to which they relied on procedural computation, online transformation of numerical information, and retrieval of arithmetic facts. These distinctions were reflected in the overall behavioral pattern and provided an empirical basis for the subsequent functional analysis of operation-specific differences. In this respect, the behavioral data support the view that arithmetic activity is internally differentiated and cannot be regarded as a single homogeneous form of mathematical processing.

Thus, the behavioral results confirm that the experimental design successfully manipulated the principal parameters relevant to the research hypotheses, namely task difficulty, operation type, and subjective metacognitive evaluation of mental effort. These findings provide an important psychological basis for the interpretation of the neuroimaging results presented below, because they show that changes in functional activation were associated with clearly differentiated task conditions and with systematic variation in the subjective experience of cognitive load.

Table 4. Behavioral Results

Participant	Total Number of Answers	Total Number of Correct Answers	Total Accuracy percentage [%]	Minimum Reaction time [s]	Maximum Reaction time [s]
01	376	274	72.87	0.8539	23.1232

02	429	422	98.25	0.6698	28.2803
03	439	407	92.71	0.5526	26.9577
04	551	539	97.82	0.6363	16.8109
05	262	164	62.60	0.9711	31.5622
06	624	577	92.47	0.5191	15.6221
07	458	432	94.32	0.7200	26.2879
08	394	369	93.65	0.8539	31.3780
09	483	460	95.24	0.6195	31.4784
10	463	428	92.44	0.6363	23.8431
11	443	401	90.52	0.7032	20.5445
12	261	247	94.64	1.2893	31.1432
13	282	276	97.87	0.7870	11.7038
14	542	504	92.99	0.7535	18.0499
15	337	295	87.54	1.0381	20.2431
16	321	294	91.59	0.7032	25.8690
17	518	474	91.51	0.5861	14.5168
18	629	619	98.41	0.5860	22.7884
19	470	348	74.04	0.4856	13.0937
20	326	307	94.17	0.9042	25.9195

2.3.2. Functional Correlates of Metacognitive Monitoring of Subjective Mental Effort

The second stage of the analysis focused on the functional correlates of metacognitive monitoring, operationalized in the present study as the subjective evaluation of mental effort following mathematical task performance. The results showed that metacognitive evaluation engaged a distributed network of regions associated with cognitive control, performance monitoring, self-referential processing, and interoceptive awareness. The principal activations observed during metacognitive evaluation are summarized in **Tables 5-6** (with the complete dataset available in Supplementary Tables

S1–S57), and their spatial distribution is illustrated in Figure 4 as well as in the representative activation map presented in Figure 5.

The most prominent activations were observed in prefrontal cortical regions, including the bilateral middle frontal gyri, as well as in the dorsal anterior cingulate cortex, bilateral insula, precuneus, and posterior cingulate regions. This pattern indicates that metacognitive monitoring of mental effort depends on functional systems involved in assessing task demands, monitoring the adequacy of performance, and integrating subjective information about cognitive load. The participation of posterior midline regions further suggests the involvement of reflective and self-referential processes in the evaluation of expended effort.

From the standpoint of cognitive psychology, these findings are important because they show that subjective mental effort should not be understood merely as a verbal report about task experience. Rather, it appears to reflect a metacognitive process that is embedded in broader systems of cognitive regulation. The involvement of frontal, cingulate, and insular regions suggests that effort evaluation is closely linked to the monitoring of uncertainty, conflict, and resource expenditure during demanding cognitive activity.

Accordingly, the obtained data support the assumption that subjective mental effort constitutes a psychologically meaningful and functionally grounded metacognitive indicator. This conclusion is essential for the general logic of the dissertation, since the metacognitive monitoring of effort is treated here as one of the key mechanisms linking the object-level of mathematical problem solving with the meta-level of cognitive regulation.

Table 5: Summary of Key Activations for Metacognition Tasks

Brain Region	Left Hemisphere Clusters	Right Hemisphere Clusters	Key Areas
Prefrontal Cortex	54	40	Inferior, Middle, Superior Frontal Gyrus
Parietal Cortex	6	11	Inferior Parietal Lobule
Cingulate Cortex	3	12	Anterior & Posterior Cingulate
Precuneus	10	12	Precuneus
Insula	5	7	Insula

Table 6. Brain Activations Associated with Metacognitive Evaluation

Brain Region	Hemisphere	Functional Role
Prefrontal Cortex	Left and Right	Explicit self-evaluation and cognitive control
Dorsal Anterior Cingulate Cortex (dACC)	Bilateral	Conflict monitoring and performance monitoring
Anterior Insula	Bilateral	Subjective experience of mental effort and interoceptive awareness
Precuneus	Bilateral	Self-referential processing and reflective evaluation

Figure 4. Clusters representation for the contrast metacognition task of the addition minus control task

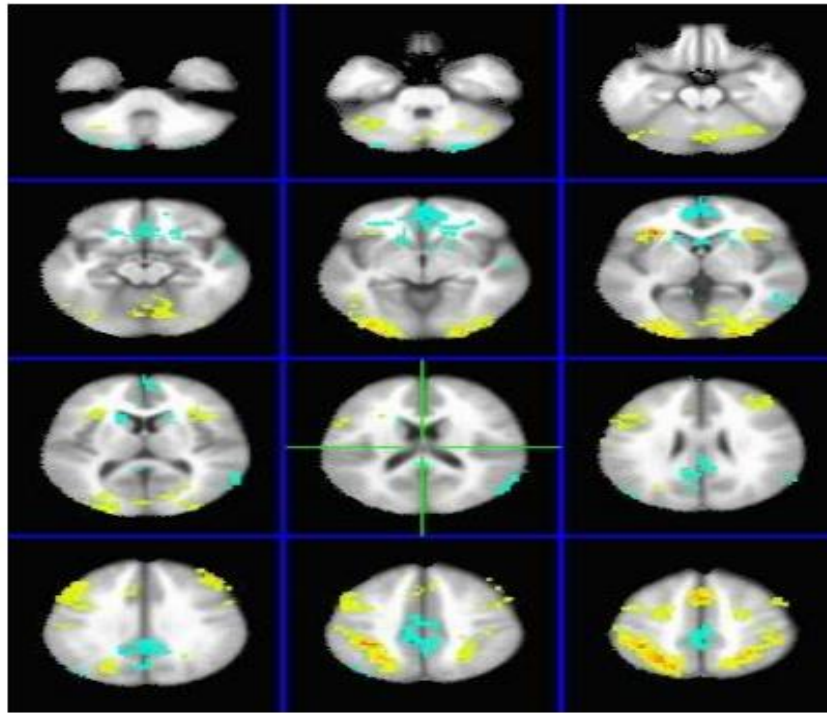
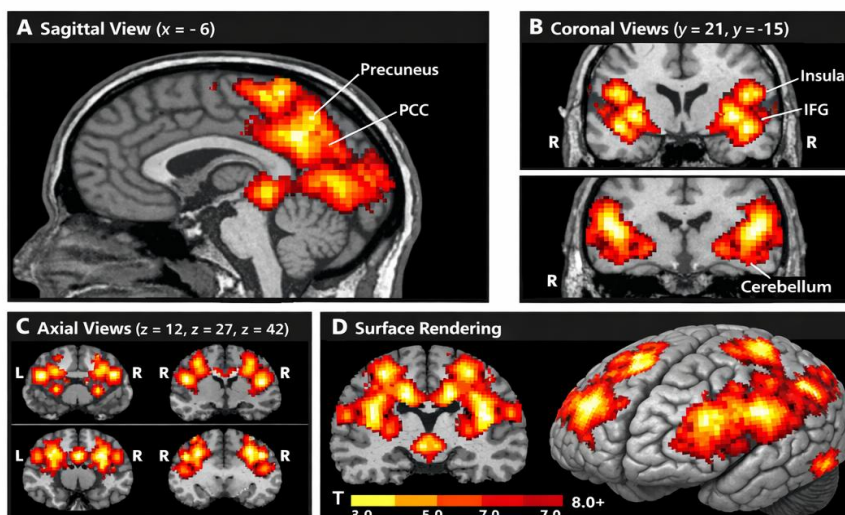


Figure 5. Brain regions significantly activated during metacognitive evaluation of mental effort [contrast: all metacognitive tasks > fixation]. Statistical maps are thresholded at voxel-wise FDR $p < 0.01$ with cluster-extent correction ($p < 0.001$). Activations are overlaid on a standard MNI template brain. The color bar indicates t -statistic values.



Statistical parametric maps showing regions significantly activated during metacognitive rating of mental effort compared to fixation baseline (contrast: all metacognitive tasks > fixation). Clusters were thresholded at voxel-wise FDR $p < 0.01$ with cluster-extent correction ($p < 0.001$).

(A) Sagittal view ($x = -6$) reveals activation in medial prefrontal cortex, anterior cingulate, precuneus, and cerebellar regions. (B) Coronal views ($y = 21$, $y = -15$) demonstrate bilateral insular cortex engagement, inferior frontal gyrus activation, and cerebellar involvement. (C) Axial views ($z = 12$, $z = 27$, $z = 27$, $z = 42$) show extensive bilateral prefrontal activation, cingulate cortex, basal ganglia, and superior parietal/precuneus clusters. (D) Surface rendering provides a three-dimensional overview of the distributed fronto-cingulo-insular-precuneus network supporting metacognitive effort appraisal.

2.3.3. Functional Correlates of Mathematical Cognition

The next stage of the analysis examined the functional organization of mathematical cognition during arithmetic problem solving. Mathematical task performance was associated with robust activation in a distributed fronto-parietal-temporal network implicated in numerical processing, symbolic transformation, executive regulation, and arithmetic performance. The main activations associated with mathematical cognition are presented in **Table 7-8** (full results are in Supplementary Tables S58–S94), while representative activation maps are shown in Figure 6-7.

Strong bilateral activation was observed in inferior and middle frontal regions, the cingulate cortex, parietal cortical areas, the precuneus, and temporal regions. Of particular importance was the involvement of areas associated with symbolic and quantitative information processing, including parietal regions linked to magnitude manipulation and temporal areas implicated in the retrieval of arithmetic facts and symbolic numerical representations. This pattern confirms that mathematical cognition relies not only on general systems of cognitive control, but also on specialized processing mechanisms specific to arithmetic activity.

In psychological terms, these data indicate that mathematical problem solving constitutes a complex and hierarchically organized form of cognitive activity. Its successful implementation requires the integration of several components: executive regulation of performance, maintenance and transformation of symbolic information, processing of quantitative relations, retrieval of stored arithmetic knowledge, and strategic control over task execution. Thus, mathematical cognition should be regarded as a multicomponent system rather than as a unitary computational process.

These findings are consistent with the hypothesis that mathematical cognition includes domain-specific mechanisms in addition to the domain-general systems involved in monitoring and control. This point is theoretically important because it supports the proposition that mathematical thinking has its own specific functional organization, even though it remains embedded in broader mechanisms of cognitive regulation.

Table 7: Summary of Key Activations for Mathematical Tasks

Brain Region	Left Hemisphere Clusters	Right Hemisphere Clusters	Key Areas
Prefrontal Cortex	81	49	Inferior, Middle, Superior Frontal Gyrus
Temporal Cortex	14	11	Inferior, Middle, Superior Temporal Gyrus
Cingulate Cortex	12	4	Anterior & Posterior Cingulate
Precuneus	12	15	Precuneus
Insula	4	2	Insula

Table 8. Brain Activations Associated with Mathematical Cognition

Brain Region	Hemisphere	Functional Role
Intraparietal Sulcus (IPS)	Left and Right	Numerical magnitude processing and quantity representation
Inferior Frontal Gyrus (IFG)	Predominantly left	Symbolic processing and arithmetic manipulation
Temporal Cortex	Predominantly left	Retrieval of arithmetic facts from long-term memory
Dorsal Anterior Cingulate Cortex (dACC)	Bilateral	Monitoring task difficulty and cognitive control

Strong bilateral activation was found in the inferior frontal gyri and the middle frontal gyri. The precuneus and cingulate gyri were also engaged. Crucially, and as predicted, mathematical tasks specifically elicited activation in bilateral temporal cortices, a region not prominently active during the metacognitive ratings alone.

Figure 6. Clusters representation for the contrast mathematical task of division difficulty level 2 minus fixation.

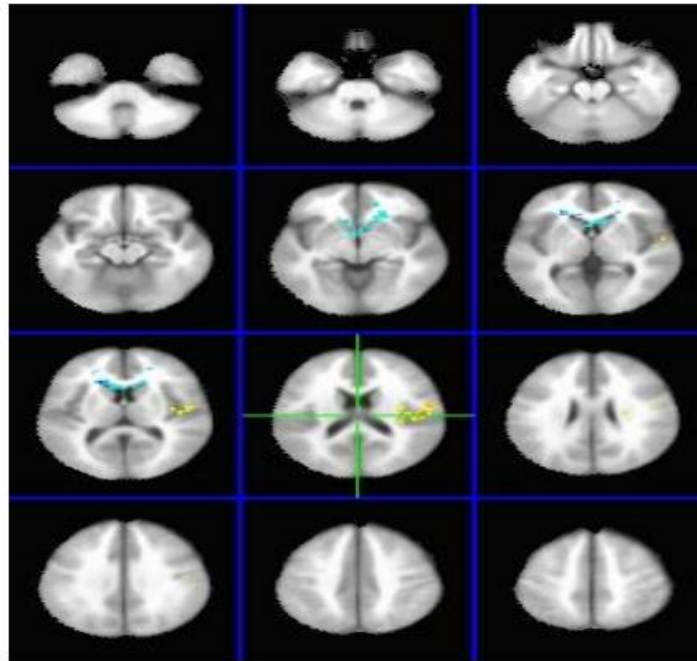
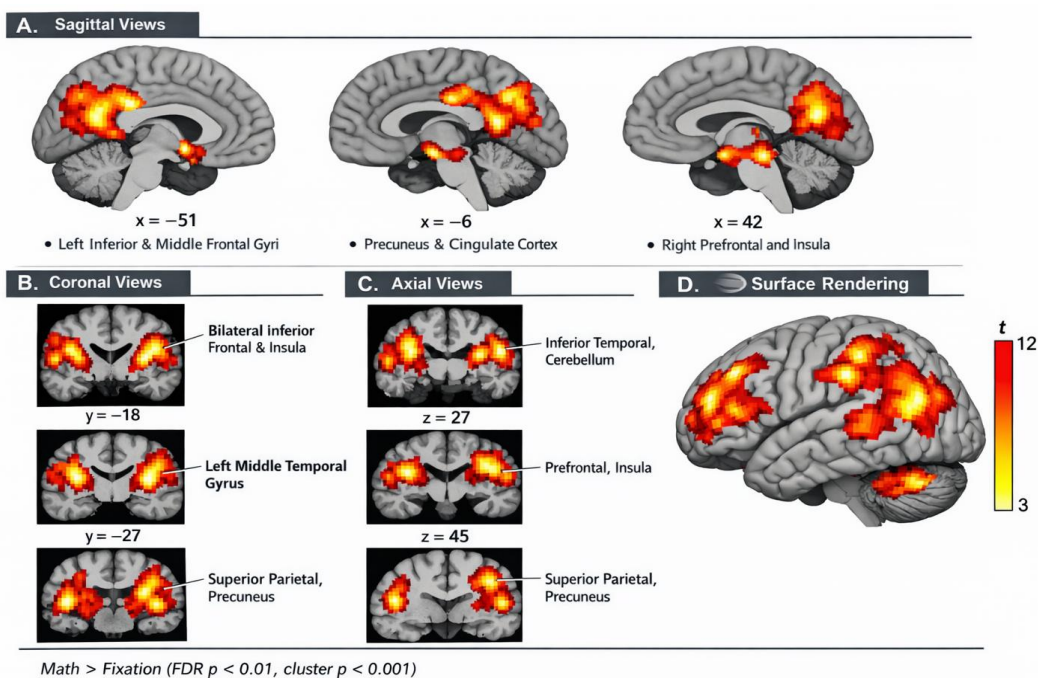


Figure 7. Brain regions significantly activated during mathematical problem-solving (contrast: division task, difficulty level 1 > fixation). Statistical maps are thresholded at voxel-wise FDR $p < 0.01$ with cluster-extent correction ($p < 0.001$). Activations are overlaid on a standard MNI template brain. The color bar indicates t -statistic values.



2.3.4. Shared and Functionally Specific Mechanisms of Metacognitive Monitoring and Mathematical Cognition

A central objective of the empirical study was to determine the degree of overlap and differentiation between metacognitive monitoring and mathematical cognition. The analysis demonstrated that these processes rely on partially overlapping functional systems while at the same time preserving a clear degree of specificity. The general pattern of overlap is illustrated in Table 9 and Figure 9, whereas the broader relation between shared and distinct systems is summarized in Figure 8.

Both metacognitive evaluation and mathematical task performance engaged prefrontal cortical areas, the dorsal anterior cingulate cortex, insula, precuneus, and posterior cingulate regions. This convergence suggests that both forms of activity depend on common mechanisms involved in monitoring task demands, evaluating uncertainty, regulating attention, and allocating cognitive resources. In this sense, metacognitive monitoring and mathematical cognition cannot be regarded as entirely separate systems; rather, they are functionally integrated through shared mechanisms of cognitive control.

At the same time, mathematical cognition additionally recruited domain-specific systems associated with symbolic and quantitative processing, especially parietal and temporal regions that were not equally prominent during metacognitive evaluation. This dissociation indicates that the overlap between the two domains is partial rather than complete. Accordingly, the results support the central proposition of the dissertation that metacognitive monitoring and mathematical cognition represent interrelated but functionally distinct levels of cognitive organization.

This conclusion is particularly important because it allows the obtained results to be interpreted within the framework of a two-level model of cognitive activity. Within this model, mathematical problem solving may be regarded as the object-level of information processing, whereas metacognitive monitoring functions at the meta-level, providing evaluation, control, and regulation of ongoing performance. The empirical data therefore support not only the existence of interaction between these processes, but also their functional differentiation within a common cognitive architecture.

Table 9. Brain regions showing significant activation during mathematical problem solving and metacognitive evaluation of subjective mental effort (random-effects analysis, $p < .01$ FDR corrected, cluster threshold $p < .001$).

Brain Region	Hemisphere	MNI Coordinates (x y z)	Cluster Size (voxels)	Peak t-value	Associated Process
Dorsal Anterior Cingulate Cortex (dACC)	Bilateral	4 24 36	142	5.21	Metacognitive monitoring / cognitive control
Anterior Insula	Right	34 20 2	128	4.97	Subjective mental effort evaluation
Dorsolateral Prefrontal Cortex (DLPFC)	Left	-42 36 30	116	4.63	Executive control and effort regulation
Inferior Frontal Gyrus (IFG)	Left	-46 18 10	104	4.41	Symbolic processing in mathematical tasks
Intraparietal Sulcus (IPS)	Bilateral	-30 -56 44	158	5.48	Numerical magnitude processing
Temporal Cortex (Middle / Inferior Temporal Gyri)	Left	-54 -46 -6	121	4.35	Retrieval of arithmetic facts
Precuneus	Bilateral	6 -64 38	133	4.72	Self-referential processing and reflective evaluation
Posterior Cingulate Cortex	Bilateral	2 -52 26	109	4.26	Integration of internal monitoring signals

Figure 8. Neural activation during mathematical problem solving and metacognitive evaluation of mental effort.

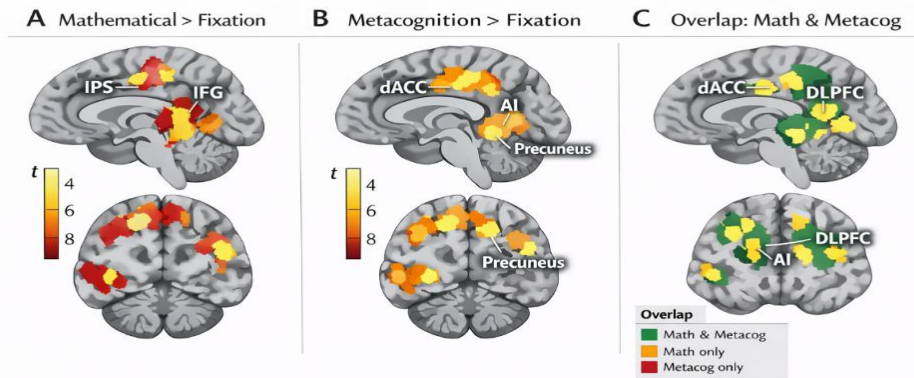
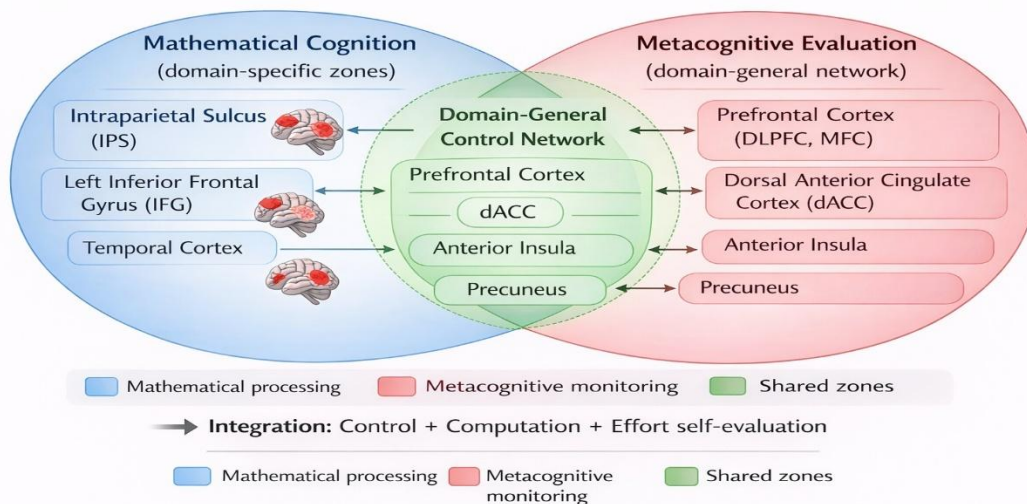


Figure 9. Overlap of Neural Networks of Metacognition and Mathematical Cognition



2.3.5. Domain-Specific Functional Contributions to Mathematical Cognition

Further analysis demonstrated that, in addition to the shared control-related systems described above, mathematical cognition depends on domain-specific functional mechanisms. These mechanisms were most clearly reflected in the activation of bilateral parietal and temporal regions associated with numerical magnitude representation, symbolic computation, and retrieval of arithmetic facts. The corresponding activation pattern is illustrated in the domain-specific maps presented in Figure 10.

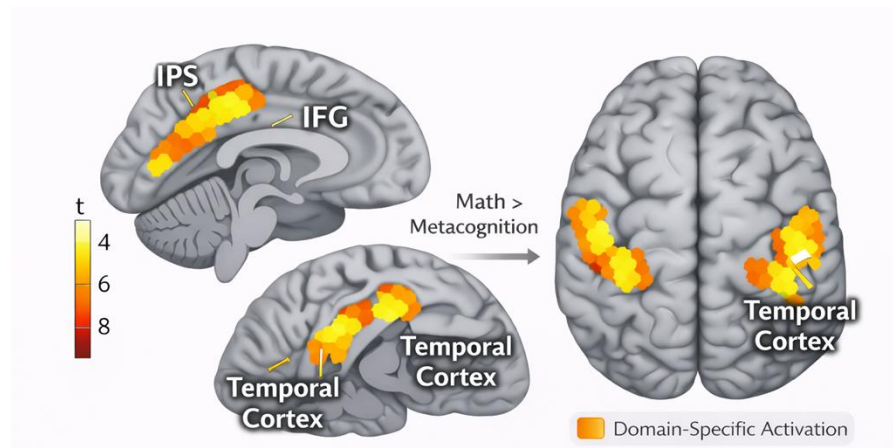
The additional involvement of temporal cortical regions is of particular importance. These regions were considerably less pronounced during metacognitive evaluation, which suggests that they contribute specifically to symbolic-semantic and memory-

related components of arithmetic processing. At the same time, parietal regions appear to play a substantial role in magnitude-based and procedural aspects of calculation. This combination of temporal and parietal engagement supports the view that mathematical problem solving requires multiple specialized forms of information processing.

These findings confirm the hypothesis that mathematical cognition cannot be reduced to general mechanisms of cognitive control, even though such mechanisms are clearly involved in the performance of demanding arithmetic tasks. Rather, mathematical thinking appears to emerge from the interaction between domain-general systems of regulation and domain-specific mechanisms of symbolic and quantitative processing.

In theoretical terms, this result is important because it supports the characterization of mathematical cognition as a specific domain of intellectual activity embedded in a broader structure of self-regulated cognition. Thus, the domain specificity of arithmetic processing does not contradict the role of metacognition in its regulation, but instead clarifies the level at which metacognitive monitoring interacts with mathematical operations.

Figure 10. Domain-specific neural activation during mathematical cognition



2.3.6. Effects of Task Difficulty on Mathematical Processing and Metacognitive Monitoring

The next stage of the analysis addressed the role of task difficulty in modulating both mathematical cognition and metacognitive monitoring. The obtained results revealed a clear parametric effect of task complexity. As the objective difficulty of

arithmetic tasks increased, stronger activation was observed both in regions associated with mathematical processing and in regions involved in monitoring and cognitive control. This effect is illustrated in Figure 11 and is also reflected in the comparative activation patterns shown in Figure 12.

Increasing task difficulty was accompanied by stronger engagement of parietal and inferior frontal regions associated with numerical processing, as well as by increased activation in the dorsal anterior cingulate cortex and anterior insula. This pattern indicates that higher computational demands require not only more intensive mathematical processing but also stronger involvement of systems responsible for monitoring conflict, uncertainty, and cognitive load.

In psychological terms, this result suggests that metacognitive monitoring is dynamically embedded in mathematical problem solving and becomes increasingly relevant as task performance grows more demanding. The parametric character of this effect is particularly important because it demonstrates that the relation between mathematical cognition and metacognitive control is not static. On the contrary, the involvement of monitoring mechanisms varies systematically depending on the level of objective task complexity.

These findings are directly consistent with the hypothesis that the engagement of metacognitive mechanisms increases as a function of mathematical difficulty. They also support the interpretation of subjective mental effort as an indicator of cognitive load that reflects the interaction between computational demand and regulatory control during performance.

Figure 11. Parametric modulation of neural activity by task difficulty.

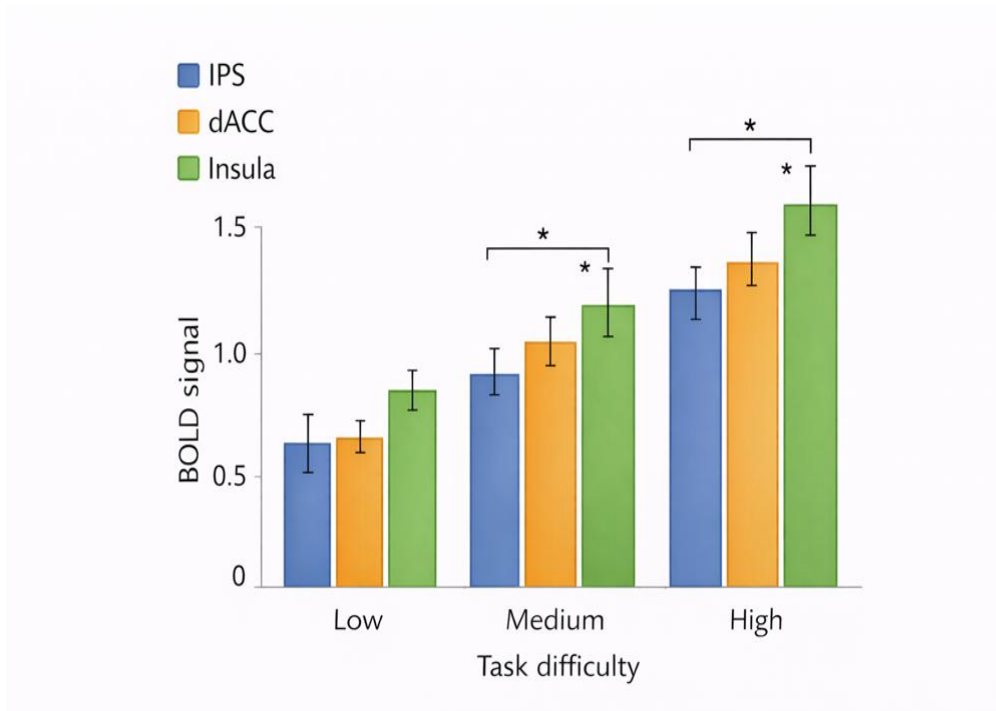
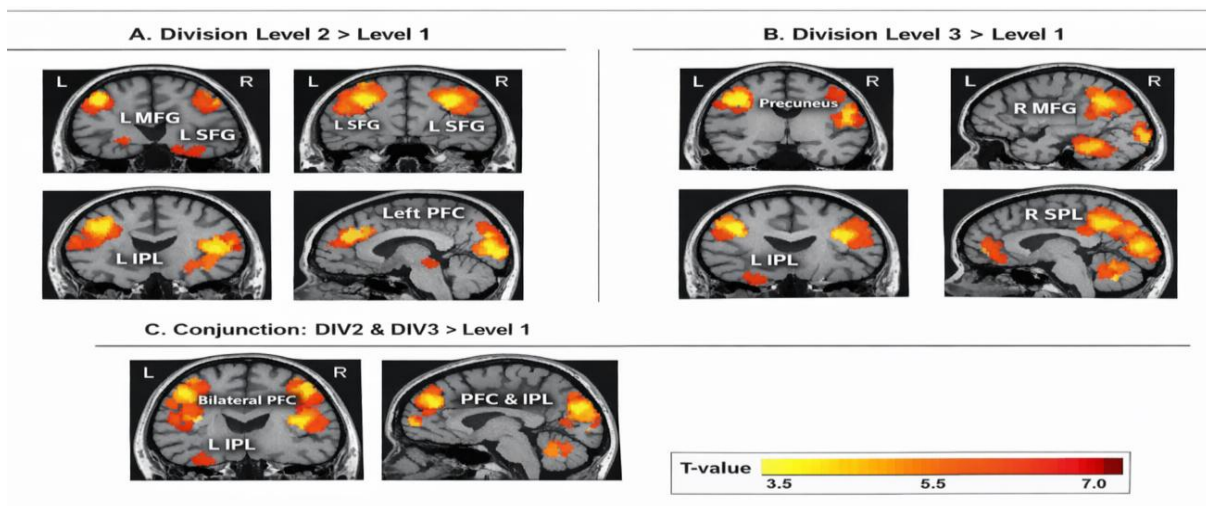


Figure 12. Neural activation increases with arithmetic difficulty. Axial and sagittal slices showing brain regions with significantly greater BOLD signal for difficult (Level 3) compared to easy (Level 1) division problems. Statistical maps are thresholded at $p < 0.01$ FDR corrected with a cluster-extent threshold of $p < 0.001$. Activation is observed in classic mathematical processing



2.3.7. Functional Differences Across Arithmetic Operations

An additional objective of the empirical study was to examine whether different arithmetic operations are associated with distinct cognitive strategies and

correspondingly differentiated functional profiles. The obtained data indicate that, although all arithmetic operations engaged a common fronto-parietal system associated with numerical cognition, specific differences were observed across operation types. These differences are illustrated in Figure 13-14 and are reflected in the comparative analyses presented in the text.

Multiplication and division tasks were associated with relatively stronger involvement of temporal cortical regions, suggesting a greater contribution of memory retrieval and access to stored arithmetic knowledge. By contrast, addition and subtraction showed relatively stronger reliance on parietal mechanisms associated with magnitude manipulation, procedural computation, and the online transformation of numerical information. This pattern indicates that different arithmetic operations rely on partially distinct cognitive strategies within a broader common system of mathematical processing.

From the standpoint of cognitive psychology, these findings are highly significant because they demonstrate that mathematical cognition is internally differentiated. Arithmetic activity is not organized as a single undifferentiated process, but rather includes multiple forms of information processing that differ in their functional demands and strategic organization. This conclusion supports the hypothesis that addition, subtraction, multiplication, and division impose different regulatory and computational requirements.

The obtained data therefore clarify the internal structure of mathematical cognition and provide a more precise account of how specific arithmetic operations are implemented within a common functional architecture. This result also has broader theoretical significance because it refines the notion of mathematical thinking as a multicomponent and hierarchically organized form of cognitive activity.

Figure 13. Neural activation differences across arithmetic operations.

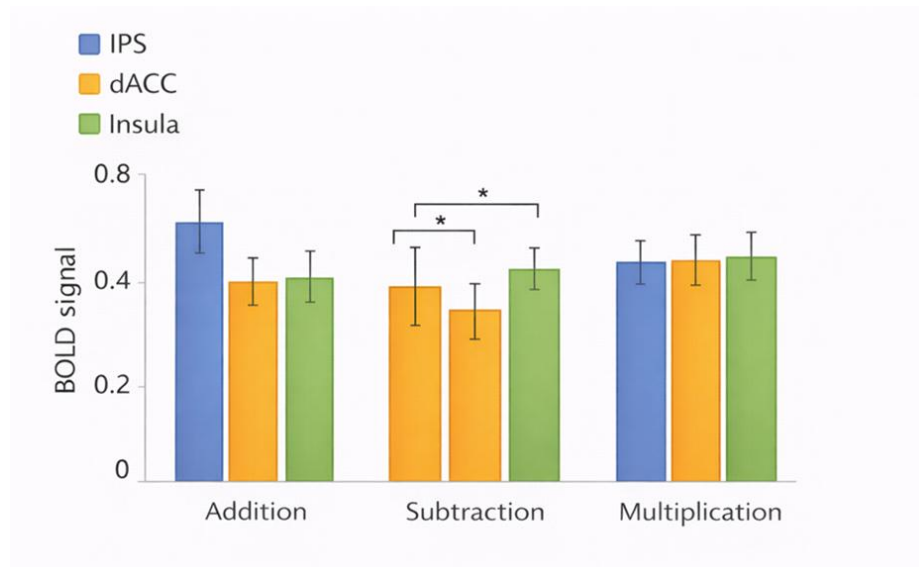
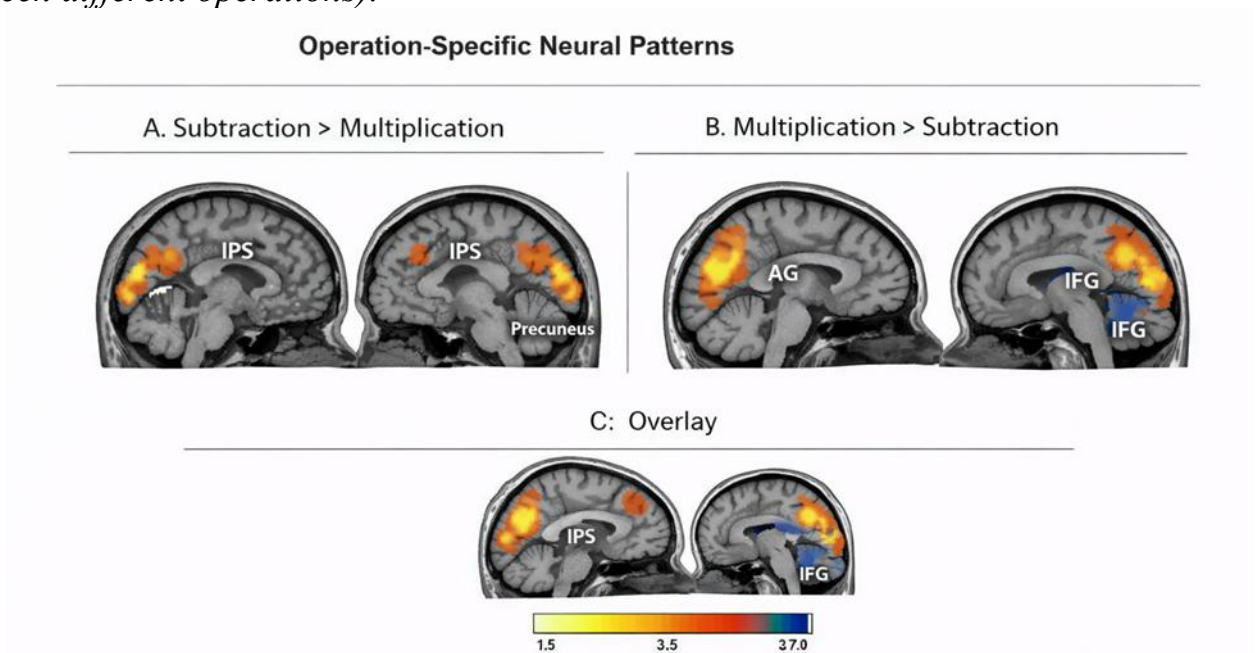


Figure 14: Operation-Specific Neural Patterns (Illustrating Dissociable Networks for Subtraction and Multiplication) Source Data: Table S105 (coordinates for contrasts between different operations).



Statistical parametric maps displaying regions with greater activation for subtraction compared to multiplication (Panel A) and for multiplication compared to subtraction (Panel B), thresholded at $p < 0.01$ FDR corrected. Subtraction preferentially engages bilateral intraparietal sulcus regions (IPS) consistent with magnitude-based procedural processing. In contrast, multiplication shows greater recruitment of the left angular gyrus (AG) and left inferior frontal gyrus (IFG), areas associated with arithmetic fact retrieval and verbal processing. This double dissociation supports models positing distinct neural pathways for different arithmetic operations.

2.3.8. Subjective Mental Effort as a Metacognitive Indicator of Cognitive Load

A key aim of the study was to test whether subjective ratings of mental effort correspond to identifiable functional correlates associated with metacognitive monitoring. The results support this assumption. Subjective effort ratings were systematically associated with activation in regions involved in conflict monitoring, cognitive control, interoceptive awareness, and reflective evaluation. The principal regions associated with effort monitoring are summarized in Table 10, and the corresponding activation pattern is illustrated in Figure 15.

The most relevant regions included the dorsal anterior cingulate cortex, anterior insula, lateral prefrontal cortex, precuneus, and inferior parietal cortex. Their involvement suggests that subjective mental effort reflects not only a conscious impression of task difficulty, but also a broader system of metacognitive regulation integrating information about task demands, performance requirements, and the availability of cognitive resources. The participation of posterior midline regions further implies that effort evaluation includes a reflective component through which the individual interprets current performance in relation to internal states and previous task experience.

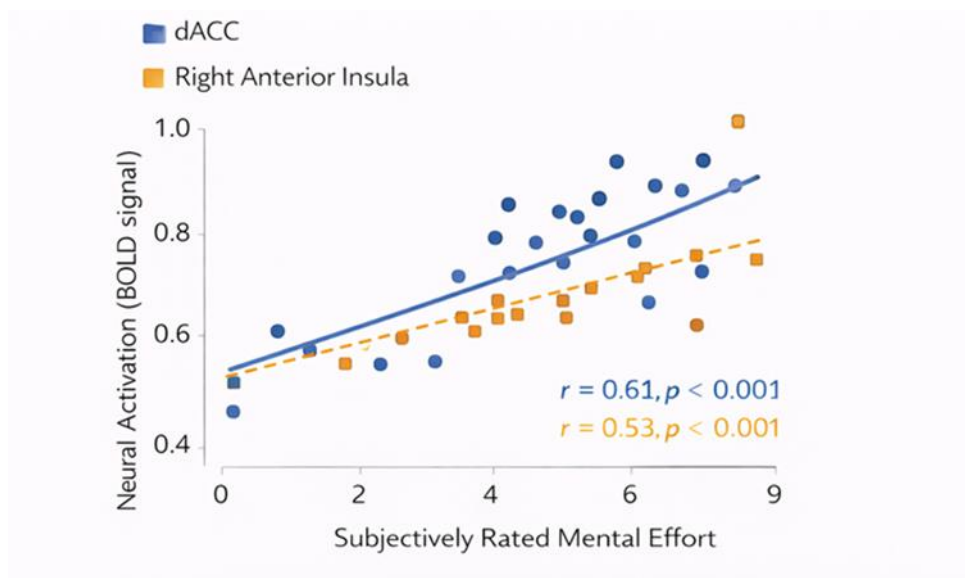
Thus, the findings provide empirical support for the treatment of subjective mental effort as a valid metacognitive indicator of cognitive load. In the context of the present dissertation, this result is of central importance because it substantiates the role of mental effort as a key mechanism linking object-level mathematical processing with meta-level monitoring and regulation. The results therefore reinforce the general theoretical position advanced in the study, according to which metacognitive monitoring is not external to mathematical cognition, but embedded in its functional organization.

Table 10. Neural Correlates of Subjective Mental Effort

Brain Region	Hemisphere	Functional Role in Effort Monitoring
Dorsal Anterior Cingulate Cortex (dACC)	Bilateral	Monitoring cognitive conflict and task demands; regulation of cognitive control
Anterior Insula	Bilateral	Interoceptive awareness and subjective experience of mental effort

Brain Region	Hemisphere	Functional Role in Effort Monitoring
Lateral Prefrontal Cortex (DLPFC)	Predominantly bilateral	Allocation of cognitive resources and executive control
Precuneus	Bilateral	Self-referential processing and reflective evaluation of task performance
Inferior Parietal Cortex	Bilateral	Integration of cognitive load and attentional resources

Figure 15. Correlation between subjective mental effort ratings and neural activation in metacognitive control regions.



2.3.9. ROI Analysis of Key Regions Involved in Cognitive Control and Mathematical Processing

To further clarify the functional organization of the processes under investigation, a region-of-interest analysis was conducted. BOLD signal values were extracted from regions associated with cognitive control and metacognitive evaluation, including the inferior frontal gyrus, middle frontal gyrus, anterior cingulate cortex, cingulate gyrus, and insula. The extracted values are presented in Table 11 and Figure 16.

The ROI analysis confirmed that the engagement of these regions varied as a function of both operation type and difficulty level. This result provides additional support for the view that mathematical cognition and metacognitive monitoring interact through a system of partially overlapping functional mechanisms whose relative

contribution changes depending on task demands. In particular, activity in control-related regions proved to be sensitive both to the structure of the arithmetic task and to the subjective evaluation of effort.

This finding is theoretically significant because it demonstrates that the interaction between mathematical and metacognitive processes is not merely global in character, but can also be traced at the level of specific control-related regions involved in the regulation of cognitive activity. Thus, the ROI data complement the whole-brain results by showing more precisely how the balance between computational and regulatory processes changes under different experimental conditions.

At the same time, the ROI analysis strengthens the interpretation of metacognitive monitoring as an integral regulatory process embedded within mathematical cognition. The observed sensitivity of control-related regions to both task structure and subjective effort is fully consistent with the general model proposed in the dissertation.

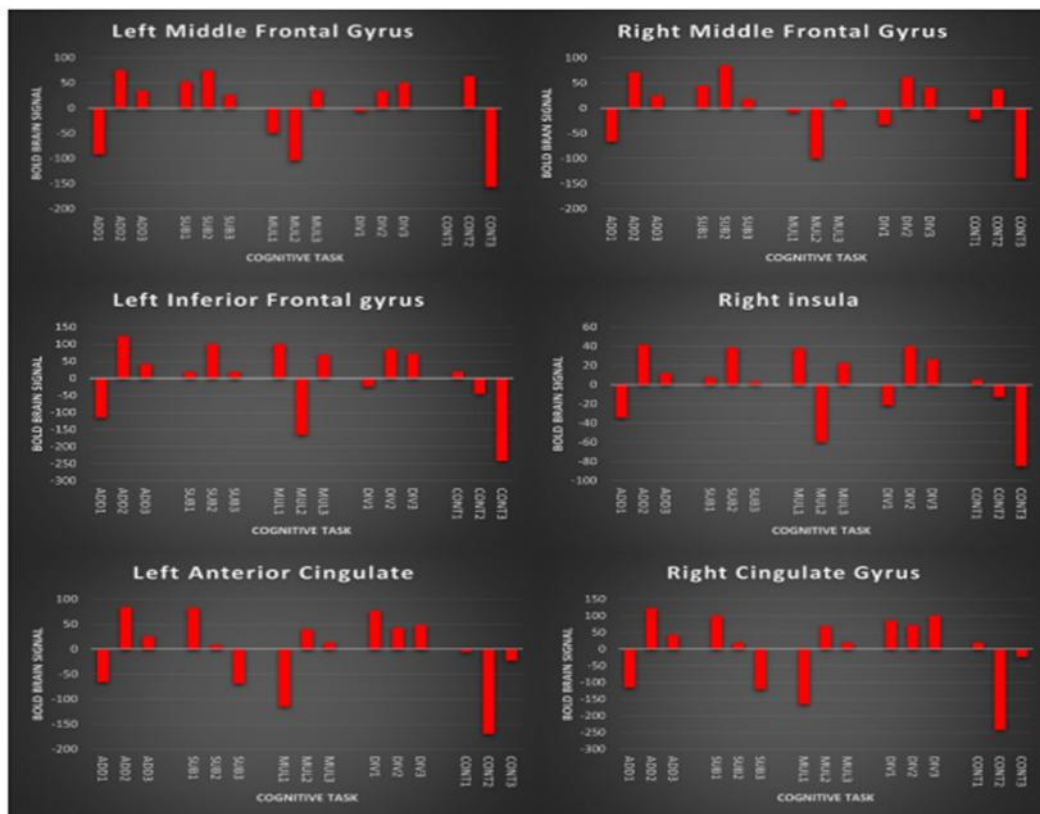
Table 11. BOLD brain signal extracted from regions of interest.

Metacognitive task	Left IFG	Left MFG	Right MFG	Right CG	Left AC	Right INS
ADD1	-114.82	-91.9	-66.45	-114.82	-65.59	-34.33
ADD2	123.19	75.48	71.54	123.19	84.23	41.42
ADD3	42.39	34.3	24.98	42.39	26.0	12.0
SUB1	19.68	52.47	44.86	100.66	82.75	7.6
SUB2	100.66	74.78	84.75	19.73	8.13	38.59
SUB3	19.73	26.17	18.16	-120.38	-68.61	3.26
MUL1	100.67	49.54	-7.97	-165.1	-114.82	37.8
MUL2	-165.1	-103.97	-99.71	69.13	39.78	-59.46

MUL3	69.13	35.3	16.98	19.68	13.36	22.53
DIV1	-23.93	-6.21	-32.43	86.57	77.01	-21.58
DIV2	86.57	33.68	62.42	72.05	43.01	39.77
DIV3	72.05	50.04	40.74	100.67	48.37	26.2
CON1	19.65	0.63	-22.77	19.65	-5.41	5.24
CON2	-46.08	63.52	37.24	-242.79	-169.71	-13.01
CON3	-242.79	-156.83	-139.34	-23.93	-22.6	-84.67

Note: IFG – Inferior Frontal Gyrus; MFG – Middle Frontal Gyrus; CG – Cingulate Gyrus; AC – Anterior Cingulate; INS – Insula

Figure 16. BOLD brain signal for the contrast between the metacognition task and the font control task of difficulty level 1



2.3.10. Hemispheric Organization of Mathematical and Metacognitive Processes

The final stage of the analysis concerned hemispheric organization. The results revealed clear differences between mathematical cognition and metacognitive monitoring with respect to lateralization. These differences are summarized in Table 12.

Metacognitive evaluation was characterized by a relatively bilateral pattern of activation involving frontal, cingulate, insular, and posterior midline regions. Mathematical processing also showed bilateral engagement of fronto-parietal systems, but with more pronounced left-hemispheric specialization, especially in inferior frontal and temporal regions associated with symbolic processing and arithmetic fact retrieval. This pattern suggests that mathematical cognition is more strongly tied to left-lateralized symbolic and language-related systems, whereas metacognitive monitoring is implemented through a more distributed bilateral network supporting integrative and self-reflective functions.

These findings support the hypothesis that mathematical cognition and metacognitive monitoring differ in their hemispheric organization. More broadly, they reinforce the conclusion that the two processes, while tightly interconnected, remain functionally distinct and occupy different positions within the overall architecture of cognitive activity. The hemispheric analysis therefore provides an additional level of evidence for the differentiation between object-level mathematical processing and meta-level monitoring and regulation.

Thus, the results of the empirical study, taken as a whole, demonstrate that metacognitive monitoring of subjective mental effort and mathematical cognition form a functionally integrated yet differentiated system. Their interaction is expressed in the engagement of shared mechanisms of cognitive control, while their specificity is reflected in the distinct functional contributions of numerical-symbolic processing, operation-related cognitive strategies, and hemispheric organization. These findings provide empirical support for the general logic of the dissertation and create the basis for the interpretive discussion presented in the following section.

Table 12. Hemispheric Lateralization Patterns in Mathematical and Metacognitive Tasks

Cognitive Domain	Pattern of Lateralization
Mathematical Cognition	Predominantly left-hemispheric activation (Inferior Frontal Gyrus, temporal cortex)
Metacognitive Evaluation	Bilateral fronto-cingulo-insular network

2.4 Discussion

The purpose of the empirical study was to investigate the interaction between metacognitive monitoring of subjective mental effort and mathematical cognition, and to clarify the functional mechanisms underlying this interaction within a unified experimental paradigm. In accordance with the general logic of the dissertation, the study was based on the assumption that mathematical problem solving and metacognitive monitoring constitute interrelated yet functionally distinct levels of cognitive activity. The obtained results provide substantial support for this assumption and make it possible to interpret the empirical findings within the framework of a two-level model of cognitive organization, in which mathematical cognition operates at the object-level of processing, whereas metacognitive monitoring functions at the meta-level of evaluation, control, and regulation.

First, the results support the general hypothesis that metacognitive monitoring of mental effort and mathematical cognition are not independent processes, but form an integrated system of cognitive activity. The empirical data indicate that the solution of arithmetic problems and the subsequent evaluation of subjective effort engage partially overlapping functional systems associated with monitoring, control, and regulation. In this respect, the present findings are consistent with contemporary approaches to metacognition that conceptualize monitoring not as a secondary or external process, but as a constitutive component of cognitive activity itself [46, 144, 67]. The data obtained in the present study extend this view to the domain of mathematical cognition and show that metacognitive monitoring is embedded in the organization of mathematical thinking rather than merely accompanying it.

This conclusion is especially important in light of the literature reviewed in Chapter 1. Previous studies have shown that metacognitive monitoring has most often been examined in perceptual, memory, and decision-making tasks [46, 144], whereas research on mathematical cognition has focused primarily on the mechanisms of numerical representation, symbolic processing, and arithmetic computation [109, 66, 83]. As a result, the interaction between these two domains has remained insufficiently explored. The present study contributes to addressing this gap by demonstrating, within a single experimental design, that mathematical processing and metacognitive evaluation are functionally linked and should be considered jointly when analyzing the organization of complex intellectual activity.

Second, the results support the hypothesis that metacognitive monitoring and mathematical cognition rely on partially overlapping mechanisms of cognitive control. The observed convergence of activation in frontal, cingulate, insular, and posterior midline regions indicates that both mathematical problem solving and metacognitive effort evaluation depend on common systems involved in uncertainty monitoring, conflict detection, task evaluation, and regulation of cognitive resources. This pattern is highly consistent with neurocognitive models of metacognition that emphasize the role of medial and lateral prefrontal cortex, dorsal anterior cingulate cortex, anterior insula, and related structures in the monitoring of one's own cognitive processes [144, 67, 85]. At the same time, the present findings show that these systems are not limited to explicitly reflective tasks, but are also engaged in the regulation of domain-specific activity such as arithmetic performance.

From a psychological perspective, this overlap may be interpreted as evidence that metacognitive monitoring of mental effort is grounded in relatively domain-general mechanisms of cognitive control. This interpretation is also in line with developmental and comparative findings suggesting that metacognitive abilities may include both domain-general and domain-specific components [18]. The present results suggest that, in the context of mathematical performance, metacognitive monitoring of effort relies on control mechanisms that are relatively general in their organization, while their specific manifestation depends on the computational and regulatory demands of the task being

performed. In this sense, the study refines the debate on the domain-generality versus domain-specificity of metacognition by demonstrating that domain-general regulatory systems can be functionally integrated with domain-specific mathematical processes.

Third, the empirical data support the hypothesis that mathematical cognition is characterized by domain-specific processing mechanisms in addition to the domain-general systems of monitoring and control. The engagement of parietal and temporal regions during arithmetic problem solving indicates that mathematical cognition cannot be reduced to general executive regulation alone. This conclusion is consistent with prior work showing the central role of the intraparietal sulcus in numerical magnitude representation and calculation-related operations, as well as the contribution of temporal cortical regions to symbolic processing and retrieval of arithmetic facts from long-term memory [109, 66, 83]. The present results therefore confirm that mathematical cognition includes a specialized functional component that distinguishes it from general metacognitive evaluation, even though the two are coordinated within a common regulatory architecture.

This point is theoretically significant because it clarifies the status of mathematical cognition within the overall structure of cognitive activity. The findings support the view that mathematical thinking should be understood as a hierarchically organized form of cognition in which domain-specific mechanisms of quantitative and symbolic processing interact with higher-order mechanisms of metacognitive regulation. Such an interpretation corresponds to contemporary cognitive-psychological approaches that regard complex intellectual activity as a multilevel system including both task-related and regulatory components [185, 97, 93]. The present study extends these conceptions by demonstrating how metacognitive monitoring of effort is incorporated into the structure of mathematical performance.

Fourth, the obtained findings support the hypothesis concerning the role of subjective mental effort as a valid metacognitive indicator of cognitive load and regulation. The behavioral results showed that subjective effort ratings varied systematically as a function of objective task difficulty, while the functional data demonstrated that these ratings were associated with the engagement of regions

implicated in cognitive control, conflict monitoring, interoceptive awareness, and self-referential evaluation. This pattern is consistent with contemporary models according to which mental effort reflects the monitoring of task demand, uncertainty, and control engagement, and serves as a signal for adaptive redistribution of cognitive resources [71, 125].

In this regard, the study confirms that subjective mental effort should not be interpreted merely as a phenomenological by-product of difficult performance. Rather, it may be viewed as a functional metacognitive signal that mediates between the current demands of the task and the regulatory processes required to maintain performance. This interpretation is consistent with closed-loop conceptions of cognitive control, in which monitoring signals arising during task execution influence subsequent allocation of attention, working memory, and executive regulation [64]. Thus, the present data substantiate the theoretical position advanced in the dissertation that subjective mental effort occupies a central place in the architecture of metacognitive monitoring and cognitive self-regulation.

Fifth, the study supports the hypothesis that the engagement of metacognitive monitoring mechanisms increases parametrically with the objective difficulty of mathematical tasks. As arithmetic problems became more complex, stronger activation was observed not only in regions associated with numerical processing but also in regions related to monitoring and control. This pattern indicates that growing computational demands are accompanied by increased involvement of regulatory processes responsible for assessing difficulty, monitoring uncertainty, and coordinating cognitive effort. Such findings are consistent with previous studies linking effort investment and cognitive control to the activity of cingulate and insular systems [71], as well as with broader approaches emphasizing the role of uncertainty monitoring in metacognitive regulation [67, 125].

The parametric character of this effect is especially important because it demonstrates that the relation between mathematical cognition and metacognitive monitoring is dynamic rather than fixed. Metacognitive monitoring is not simply present or absent during mathematical activity; instead, its contribution varies systematically

depending on the level of task demand. This result provides empirical support for the proposition, central to the dissertation, that metacognitive processes are embedded in the structure of mathematical thinking and play an active role in regulating cognitive performance under conditions of increasing complexity.

Sixth, the results support the hypothesis that different arithmetic operations are associated with different cognitive strategies and differentiated functional profiles. Although all arithmetic operations engaged a common fronto-parietal system, the observed differences between addition, subtraction, multiplication, and division indicate that arithmetic cognition is internally differentiated. The stronger involvement of temporal regions in multiplication and division is consistent with greater reliance on retrieval of stored arithmetic knowledge, whereas the relative prominence of parietal mechanisms in addition and subtraction suggests a stronger contribution of magnitude-based manipulation and procedural computation. This interpretation is consistent with previous neurocognitive work showing that distinct arithmetic operations differ in their computational demands and in the balance between retrieval-based and procedural strategies [98, 83].

From the perspective of general psychology, this finding is important because it demonstrates that mathematical cognition cannot be treated as a homogeneous process. Instead, it includes multiple forms of information processing that differ in operational structure and in the extent to which they require monitoring and control. This conclusion refines the theoretical understanding of mathematical thinking as a complex and internally differentiated form of intellectual activity. It also supports the practical assumption that arithmetic operations may place different regulatory demands on learners, which should be taken into account in educational and diagnostic contexts.

Seventh, the empirical data support the hypothesis concerning differences in hemispheric organization between mathematical cognition and metacognitive monitoring. Mathematical processing showed more pronounced left-hemispheric specialization, whereas metacognitive evaluation exhibited a more bilateral pattern of activation. This finding is in line with previous research indicating the close association of arithmetic and symbolic processing with left-lateralized fronto-temporal systems [70,

83], while metacognitive and self-evaluative processes appear to depend on more distributed networks integrating frontal, cingulate, insular, and posterior midline regions [144, 67]. The present data therefore provide additional evidence that mathematical computation and metacognitive monitoring differ not only in function, but also in broader patterns of neural organization.

At a more general level, the findings obtained in the empirical study support the integrative model proposed in the dissertation. According to this model, mathematical cognition and metacognitive monitoring interact within a hierarchical two-level architecture. At the object-level, the individual performs arithmetic operations involving symbolic and quantitative processing. At the meta-level, monitoring mechanisms evaluate task demands, uncertainty, and subjective effort, thereby influencing the regulation of attention, working memory, and executive control [79]. The results of the study provide empirical support for this model by showing both the existence of common control-related mechanisms and the preservation of functional specificity between mathematical and metacognitive processes.

The theoretical significance of these findings lies in several aspects. First, the study advances the integration of two research traditions that have often developed separately: the psychology and neuroscience of metacognition, on the one hand, and the psychology and neuroscience of mathematical cognition, on the other. Second, it refines theoretical models of metacognitive control [175, 186] by clarifying the role of subjective mental effort as both an outcome of monitoring and a regulatory signal guiding subsequent activity. Third, it contributes to the development of a multilevel conception of cognitive activity in which mathematical thinking is understood as object-level processing embedded in a broader system of metacognitive regulation. In this sense, the study extends contemporary cognitive-psychological approaches to thinking, self-regulation, and complex intellectual performance [18, 67, 85].

The practical significance of the findings also deserves emphasis. The results suggest that subjective mental effort may be used as a psychologically meaningful indicator of cognitive load in mathematical learning and problem solving. This creates opportunities for applying the findings in educational psychology, in the development of

instructional methods aimed at strengthening self-regulatory and reflective strategies, and in the design of adaptive learning systems that take into account not only task performance but also the learner's subjective experience of difficulty. Such applications may be particularly relevant for students with difficulties in mathematics or with elevated levels of mathematics anxiety, as suggested by earlier work on the relation between metacognition, control, and individual differences in mathematical performance [151, 109, 91].

At the same time, several limitations of the empirical study should be acknowledged. First, the sample size was relatively small, which is typical for task-based fMRI research but nevertheless limits the generalizability of the findings. Second, the sample consisted of young, healthy, highly educated adults and therefore does not permit direct generalization to broader populations, including children, older adults, or individuals with learning difficulties. Third, the neuroimaging design used in the study makes it possible to identify functional associations between metacognitive monitoring and mathematical cognition, but does not by itself allow firm causal conclusions to be drawn about the direction of influence between the systems involved. These limitations are consistent with broader methodological concerns that have been noted in the literature on metacognition and cognitive neuroscience [18, 66, 67].

These limitations point to several directions for future research. Further studies should include more diverse samples varying in age, educational background, and level of mathematical competence, including participants with dyscalculia, mathematics anxiety, or other forms of impaired self-regulation. It would also be promising to extend the present design using effective connectivity approaches, such as dynamic causal modeling and psychophysiological interaction analysis, in order to clarify the directional relations between the functional systems involved. In addition, causal methods such as transcranial magnetic stimulation, as well as longitudinal educational interventions, may help determine how metacognitive monitoring contributes to the development and regulation of mathematical thinking over time. These directions are in line with current trends in the study of metacognition and complex cognitive activity [66, 67, 68].

Thus, the discussion of the results demonstrates that the empirical findings obtained in the present study are theoretically coherent, empirically meaningful, and directly relevant to the main research problem formulated in the dissertation. The study shows that metacognitive monitoring of subjective mental effort constitutes a central mechanism through which mathematical cognition is regulated under conditions of varying complexity. The obtained results therefore support the interpretation of mathematical thinking as a hierarchically organized form of cognitive activity in which domain-specific processing systems operate in continuous interaction with domain-general systems of metacognitive monitoring and control.

KEY CONCLUSIONS FOR CHAPTER 2

1. The empirical study demonstrated that metacognitive monitoring of subjective mental effort and mathematical cognition constitute interrelated yet functionally distinct components of cognitive activity. Mathematical problem solving was shown to operate at the object-level of information processing, whereas metacognitive evaluation functioned at the meta-level, providing monitoring, assessment of task demands, and regulation of ongoing performance.

2. The behavioral results confirmed that the experimental design successfully manipulated the principal parameters relevant to the study, namely the objective difficulty of arithmetic tasks, the type of arithmetic operation, and the subjective evaluation of mental effort. The observed variation in effort ratings across conditions supports the view that subjective mental effort reflects meaningful differences in cognitive load rather than arbitrary introspective judgments.

3. The results showed that metacognitive monitoring of subjective mental effort relies on functional systems associated with cognitive control, performance monitoring, and reflective evaluation. The involvement of frontal, cingulate, insular, and posterior midline regions indicates that subjective mental effort constitutes a valid metacognitive indicator of the current demands imposed on cognitive activity.

4. Mathematical cognition was found to depend on a distributed fronto-parietal-temporal system that supports symbolic and quantitative processing, executive regulation, and arithmetic performance [86]. These findings confirm that mathematical thinking is a complex and hierarchically organized form of cognitive activity that cannot be reduced to a single uniform mechanism.

5. The empirical data demonstrated the existence of partially overlapping functional mechanisms underlying metacognitive monitoring and mathematical cognition. Both processes engaged common systems of monitoring, control, and resource regulation, which indicates that metacognitive processes are embedded in the structure of mathematical activity and perform an integrative regulatory function within it.

6. At the same time, the study established functional differentiation between metacognitive monitoring and mathematical cognition. Mathematical task performance

was associated with the additional involvement of domain-specific mechanisms supporting numerical magnitude representation, symbolic transformation, and retrieval of arithmetic facts, which distinguishes mathematical processing from more general forms of metacognitive evaluation.

7. A parametric relationship was identified between the objective difficulty of arithmetic tasks and the engagement of metacognitive monitoring mechanisms. As task complexity increased, stronger activation was observed both in mathematical processing systems and in systems associated with monitoring and cognitive control. This finding indicates that metacognitive regulation becomes increasingly important under conditions of greater cognitive demand.

8. The results demonstrated that different arithmetic operations are associated with different cognitive strategies and distinct functional profiles. Addition, subtraction, multiplication, and division were shown to differ in the relative contribution of procedural, magnitude-based, and retrieval-related mechanisms, which confirms the internal differentiation of mathematical cognition.

9. Subjective mental effort was shown to function as a psychologically meaningful and functionally grounded metacognitive signal. It reflects the current level of cognitive load and participates in the regulation of cognitive resources during mathematical problem solving, thereby linking the object-level of task performance with the meta-level of monitoring and control.

10. The ROI analysis confirmed that key regions involved in cognitive control and mathematical processing vary systematically as a function of operation type, task difficulty, and subjective effort evaluation. This result provides additional evidence that the interaction between mathematical cognition and metacognitive monitoring is implemented through a system of partially overlapping mechanisms whose contribution changes depending on task demands.

11. Differences were identified in the hemispheric organization of the processes under investigation. Mathematical cognition was characterized by more pronounced left-hemispheric specialization, whereas metacognitive monitoring displayed a more bilateral

pattern of functional organization. This finding further supports the conclusion that the two processes are interconnected but functionally non-identical.

Taken together, the results of the empirical study provide support for the integrative model proposed in the dissertation, according to which mathematical cognition and metacognitive monitoring interact within a hierarchically organized system of cognitive activity. The findings substantiate the role of subjective mental effort as a central metacognitive mechanism involved in the regulation of mathematical thinking under conditions of varying complexity.

CONCLUSION

The present dissertation was aimed at identifying and empirically substantiating the nature of the interaction between metacognitive processes of monitoring and control and the processes underlying mathematical cognition, as well as at clarifying their functional organization through the use of neuroimaging methods. Particular attention was paid to subjective mental effort as a metacognitive signal reflecting the monitoring and regulation of cognitive activity.

The study addressed an important problem in contemporary cognitive psychology and cognitive neuroscience. Although metacognition and mathematical cognition have each been extensively investigated, these domains have largely developed as relatively independent fields of inquiry. Metacognitive monitoring has been studied primarily in the context of perception, memory, and decision-making [144, 67], whereas research on mathematical cognition has focused mainly on the neural and cognitive mechanisms of numerical representation, symbolic processing, and arithmetic operations [83]. As a result, the interaction between metacognitive monitoring and mathematical cognition has remained insufficiently explored, especially within a unified experimental paradigm.

To address this gap, the dissertation combined theoretical analysis with an empirical neuroimaging investigation. The theoretical analysis demonstrated that metacognitive monitoring and mathematical cognition should be regarded as partially overlapping yet functionally differentiated components of cognitive activity. Metacognitive monitoring is primarily associated with systems involved in cognitive control, uncertainty monitoring, and self-evaluation, including medial and lateral prefrontal regions, the dorsal anterior cingulate cortex, the anterior insula, and related structures [144, 67, 85]. By contrast, mathematical cognition relies on a fronto-parietal-temporal network centered on the intraparietal sulcus and associated cortical regions that support numerical representation, symbolic processing, and the retrieval of arithmetic facts [109, 66, 83].

On this basis, the dissertation proposed an integrative model of the interaction between metacognitive monitoring and mathematical cognition. Within this model,

mathematical problem solving is conceptualized as the object-level of cognitive processing, whereas metacognitive monitoring operates at the meta-level, evaluating task demands, subjective mental effort, and the adequacy of ongoing performance in order to regulate cognitive activity. In this respect, the dissertation substantiates a two-level model of cognitive organization that clarifies the relationship between direct task execution and reflective regulation.

The empirical part of the study was designed to test this model using a task-based functional magnetic resonance imaging paradigm that made it possible to compare neural activation associated with arithmetic problem solving of varying complexity and the subsequent metacognitive evaluation of subjective mental effort. This unified design allowed the identification of both overlap and differentiation between the neural systems supporting mathematical cognition and metacognitive monitoring.

The results of the empirical investigation make it possible to draw the following general conclusions.

First, the findings support the general hypothesis that metacognitive monitoring of mental effort and mathematical cognition constitute interrelated yet functionally distinct levels in the organization of cognitive activity. Mathematical problem solving was shown to operate at the object-level of information processing, whereas metacognitive processes function at the meta-level, providing monitoring, evaluation of task difficulty, and regulation of ongoing cognitive performance consistent with studies of mathematical metacognition. [63, 136, 141, 144, 152]. Thus, the dissertation confirms that metacognitive monitoring is not external to mathematical thinking but is embedded in its internal structure as a regulatory mechanism.

Second, the results indicate that metacognitive monitoring and mathematical cognition rely on partially overlapping mechanisms of cognitive control. Both the evaluation of mental effort and the solution of mathematical tasks were associated with the engagement of systems implicated in monitoring uncertainty, detecting performance conflict, and regulating cognitive resources, including medial and lateral prefrontal regions, the dorsal anterior cingulate cortex, and the anterior insula consistent with studies of mathematical metacognition [67, 144]. These findings confirm the hypothesis that

metacognitive monitoring of mental effort is grounded in relatively domain-general mechanisms of cognitive control and performs an integrative regulatory function within the structure of mathematical activity.

Third, the study demonstrates that mathematical cognition is characterized by domain-specific mechanisms for the processing of quantitative and symbolic information. In addition to the engagement of domain-general control systems, mathematical problem solving was associated with the involvement of neural regions linked to numerical magnitude representation, symbolic transformation, and arithmetic fact retrieval, including the intraparietal sulcus and temporal cortical areas [109, 66, 83]. This finding confirms the hypothesis that mathematical cognition cannot be reduced to general cognitive control alone and retains its specific functional and operational organization.

Fourth, the results provide support for the hypothesis concerning the role of subjective mental effort as a valid and theoretically meaningful metacognitive indicator. Subjective effort evaluation was shown to reflect the current level of cognitive load and to serve as a regulatory signal associated with the organization of task performance. This conclusion is consistent with contemporary approaches according to which effort evaluation is linked to cognitive control, uncertainty monitoring, and the regulation of resource allocation [71, 125]. Thus, subjective mental effort should be understood not merely as a phenomenological correlate of difficulty, but as a functional component of metacognitive regulation.

Fifth, the study confirmed the hypothesis that increases in the objective difficulty of mathematical tasks are accompanied by greater engagement of metacognitive monitoring mechanisms. The identified parametric relationship between task complexity and the involvement of regulatory systems indicates that metacognitive monitoring is systematically integrated into the structure of mathematical thinking and becomes increasingly important as task demands intensify. This result is consistent with theoretical views according to which monitoring signals related to uncertainty and effort dynamically regulate the distribution of cognitive resources [71, 125].

Sixth, the findings support the hypothesis that different arithmetic operations are associated with different cognitive strategies and distinct functional profiles within the

broader system of mathematical cognition. The results suggest that multiplication and division involve stronger reliance on mechanisms associated with retrieval from long-term memory, whereas addition and subtraction depend more strongly on magnitude manipulation and procedural computation, which is consistent with current neurocognitive conceptions of arithmetic processing [83]. This confirms that arithmetic activity is internally differentiated and includes multiple forms of information processing rather than representing a single uniform mechanism.

Seventh, the study confirmed the hypothesis concerning differences in hemispheric organization between mathematical cognition and metacognitive monitoring. Mathematical processing was characterized by more pronounced left-hemispheric specialization, whereas metacognitive monitoring demonstrated a more bilateral pattern of functional organization. This finding refines current understanding of the neural architecture of the processes under investigation and supports the view that mathematical computation and reflective regulation differ not only functionally but also in their broader neurocognitive organization.

Taken together, these findings indicate that the hypotheses advanced in the dissertation have, on the whole, received empirical support and that the aim of the study and the objectives formulated on its basis have been achieved. The research has shown that the interaction between mathematical cognition and metacognitive monitoring is best understood not as a simple coexistence of two independent processes, but as a structured relationship between two interconnected levels of cognitive organization: the level of mathematical processing proper and the level of metacognitive evaluation and regulation.

The scientific novelty of the study lies in the development and empirical substantiation of an integrative cognitive model of the interaction between metacognitive monitoring and mathematical cognition, in which subjective mental effort is conceptualized as a key regulatory mechanism. The dissertation demonstrates, first, the existence of partially overlapping mechanisms underlying metacognitive and mathematical processes; second, their functional differentiation; third, the validity of subjective mental effort as an indicator of cognitive load; fourth, the parametric dependence of metacognitive engagement on task difficulty; fifth, the differentiated

organization of arithmetic operations; and sixth, the distinct hemispheric profiles of metacognitive and mathematical processes. In this respect, the study extends current knowledge concerning the functional architecture of complex cognitive activity.

The theoretical significance of the dissertation lies in its contribution to the further development of cognitive-psychological and neurocognitive conceptions of thinking, self-regulation, and metacognition [100]. The study advances the integration of two research domains—metacognition and mathematical cognition—that have often developed separately. It refines theoretical models of metacognitive monitoring and control by clarifying the functional status of subjective mental effort and by substantiating a two-level model of cognitive activity in which mathematical thinking is treated as object-level processing and metacognitive monitoring as meta-level regulation. The findings also contribute to the discussion of the domain-general and domain-specific nature of metacognitive processes by showing that metacognitive regulation relies on relatively general control mechanisms while remaining sensitive to the structural features of the cognitive domain in which it is engaged [18, 67, 85, 177].

The practical significance of the study is determined by the possibility of applying its findings in education, psychological diagnostics, and scientific-methodological practice. The data obtained may be used in the development of educational programs aimed at fostering metacognitive competencies, particularly in mathematics learning. They may also inform instructional approaches focused on the development of self-regulatory and reflective strategies of thinking, as well as the design of adaptive educational technologies that take into account not only objective task difficulty but also the learner's subjective experience of cognitive load. This may be especially relevant for students experiencing difficulties in mathematics or elevated levels of mathematics anxiety [4, 151, 109]. In addition, the findings provide a basis for the refinement of diagnostic instruments intended to assess metacognitive monitoring, effort regulation, and cognitive control in academic contexts.

At the same time, the study has several limitations that should be considered when interpreting the results. First, the sample size was relatively limited, which is typical of fMRI research but nevertheless constrains the generalizability of the findings. Second,

the participant group was relatively homogeneous and consisted of young, healthy, and highly educated adults, which limits the extension of the conclusions to broader populations. Third, although the study made it possible to identify functional associations between metacognitive and mathematical processes, the correlational nature of neuroimaging data imposes certain restrictions on causal interpretation.

These limitations define several promising directions for further research. Future studies may expand the composition of the sample in order to test the stability of the identified patterns across age groups, educational levels [176], and levels of mathematical competence, including individuals with mathematical learning difficulties. Further investigations may also employ effective connectivity analyses, including dynamic causal modeling and psychophysiological interaction analysis, to examine directional interactions between the identified functional systems. In addition, causal methods such as transcranial magnetic stimulation and longitudinal educational interventions may provide deeper insight into the role of specific brain regions in metacognitive regulation during mathematical activity [11].

In conclusion, the dissertation provides a theoretically grounded and empirically supported account of the interaction between metacognitive monitoring and mathematical cognition. It demonstrates that subjective evaluation of mental effort constitutes an essential metacognitive signal embedded within broader systems of cognitive control and involved in the regulation of mathematical thinking. By integrating theoretical analysis with empirical neuroimaging evidence, the study contributes to the advancement of cognitive psychology, cognitive neuroscience, and the psychology of mathematical cognition, while opening new perspectives for interdisciplinary research.

Acknowledgments: I would like to express my sincere gratitude to my parents for their unwavering support throughout the process of completing this thesis.

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SUPPLEMENTARY MATERIAL

Full scale of brain coordinates of metacognition.

Metacognition tasks vs fixation.

Table S1: Coordinates associated to metacognition task of addition level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
10	-60	6	33	Right Precentral Gyrus
9	54	21	-18	Left Inferior Temporal Gyrus
9	-42	42	21	Right Insula
7	9	66	-15	Left Declive

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S2: Coordinates associated to metacognition task of addition level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
9	18	66	-18	Left Declive
9	-48	48	24	Right Inferior Parietal Lobule
5	-66	30	9	Right Superior Temporal Gyrus
5	24	-18	42	Left Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S3: Coordinates associated to metacognition task of addition level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
17	3	-48	24	Left Medial Frontal Gyrus
13	-42	-24	18	Right Middle Frontal Gyrus
12	-6	-63	21	Right Superior Frontal Gyrus
8	-54	-9	48	Right Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S4: Coordinates associated to metacognition task of subtraction level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
26	48	66	42	Left Inferior Parietal Lobule
24	-45	-36	-3	Right Middle Frontal Gyrus
22	51	54	48	Left Inferior Parietal Lobule
13	15	-48	36	Left Superior Frontal Gyrus
11	-63	54	30	Right Supramarginal Gyrus
10	-48	60	51	Right Inferior Parietal Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S5: Coordinates associated to metacognition task of subtraction level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
7	-42	-18	-30	Right Superior Temporal Gyrus
5	-15	69	36	Right Precuneus
4	30	-45	36	Left Middle Frontal Gyrus
4	-18	12	69	Right Superior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S6: Coordinates associated to metacognition task of subtraction level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
14	57	48	12	Left Superior Temporal Gyrus
12	-36	84	0	Right Middle Occipital Gyrus
12	-12	-12	12	Right Caudate

12 -39 87 12 Right Middle Occipital Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S7: Coordinates associated to metacognition task of multiplication level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
27	-27	-6	12	Right Lentiform Nucleus
13	9	-12	-30	Left Rectal Gyrus
11	33	33	-3	Left Caudate
10	48	-3	15	Left Inferior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S8: Coordinates associated to metacognition task of multiplication level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
18	-24	45	66	Right Postcentral Gyrus
15	9	-51	0	Left Medial Frontal Gyrus
14	39	75	24	Left Middle Temporal Gyrus
11	-63	39	-24	Right Inferior Temporal Gyrus
10	-30	-3	-3	Right Lentiform Nucleus
10	54	36	12	Left Superior Temporal Gyrus
10	3	60	45	Left Precuneus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S9: Coordinates associated to metacognition task of multiplication level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
12	24	12	51	Left Precentral Gyrus

12	-9	90	-24	Right Uvula
10	-15	-3	-30	Right Uncus
10	3	-48	-6	Left Medial Frontal Gyrus
10	21	66	-27	Left Pyramis
10	0	66	39	Right Precuneus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S10: Coordinates associated to metacognition task of division level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
24	-6	48	-33	Right Cerebellar Tonsil
20	-51	15	33	Right Postcentral Gyrus
8	21	-39	9	Left Medial Frontal Gyrus
8	60	12	30	Left Precentral Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S11: Coordinates associated to metacognition task of division level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
22	48	21	42	Left Postcentral Gyrus
20	-45	12	30	Right Precentral Gyrus
14	-24	63	-21	Right Declive
14	-51	18	42	Right Postcentral Gyrus
11	-36	69	12	Right Middle Occipital Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S12: Coordinates associated to metacognition task of division level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
16	15	57	-15	Left Declive
13	-51	39	-42	Right Cerebellar Tonsil
13	-33	63	15	Right Middle Temporal Gyrus
12	-42	69	12	Right Middle Temporal Gyrus
12	60	12	33	Left Precentral Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S13: Coordinates associated to metacognition task of control level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
80	6	81	12	Left Cuneus
72	12	60	-3	Left Culmen
64	-51	21	21	Right Postcentral Gyrus
58	-60	-15	15	Right Inferior Frontal Gyrus
45	-24	63	-15	Right Declive
27	3	-3	48	Left Medial Frontal Gyrus
25	-51	-21	-6	Right Inferior Frontal Gyrus
25	-6	90	-3	Right Lingual Gyrus
23	-6	90	33	Right Cuneus
20	36	-21	3	Left Insula

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S14: Coordinates associated to metacognition task of control level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
26	-54	15	18	Right Postcentral Gyrus
24	-27	-18	9	Right Claustrum
14	48	-3	12	Left Precentral Gyrus
14	-21	-27	-3	Right Inferior Frontal Gyrus
12	36	-18	12	Left Insula

10 18 -27 9 Left Anterior Cingulate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S15: Coordinates associated to metacognition task of control level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
26	12	75	-12	Left Declive
14	-6	90	18	Right Cuneus
12	-27	18	42	Right Middle Frontal Gyrus
12	0	-15	-3	Right Anterior Cingulate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Metacognition tasks vs font task of control level 1.

Table S16: Coordinates associated to metacognition task of addition level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
16	57	51	-9	Left Middle Temporal Gyrus
14	36	-48	12	Left Middle Frontal Gyrus
12	6	39	6	Left Parahippocampal Gyrus
8	-27	-57	39	Right Superior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S17: Coordinates associated to metacognition task of addition level 2 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
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9	30	6	-21	Left Parahippocampal Gyrus
6	27	-6	39	Left Middle Frontal Gyrus
5	45	15	-9	Left Superior Temporal Gyrus
5	-39	30	30	Right Inferior Parietal Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S18: Coordinates associated to metacognition task of addition level 3 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
39	-24	-3	9	Right Lentiform Nucleus
38	39	-9	33	Left Middle Frontal Gyrus
28	9	-6	12	Left Caudate
13	45	-36	24	Left Middle Frontal Gyrus
10	45	-45	12	Left Middle Frontal Gyrus
10	27	-9	39	Left Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S19: Coordinates associated to metacognition task of subtraction level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
85	42	-12	27	Left Middle Frontal Gyrus
68	57	48	-6	Left Middle Temporal Gyrus
28	36	-42	9	Left Middle Frontal Gyrus
21	33	-48	18	Left Middle Frontal Gyrus
11	-12	-3	-12	Right Subcallosal Gyrus
11	3	21	15	Left Thalamus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space

with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S20: Coordinates associated to metacognition task of subtraction level 2 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
25	42	-9	27	Left Inferior Frontal Gyrus
11	42	45	48	Left Inferior Parietal Lobule
10	48	51	-6	Left Middle Temporal Gyrus
8	36	24	60	Left Precentral Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S21: Coordinates associated to metacognition task of subtraction level 3 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
67	51	54	-6	Left Inferior Temporal Gyrus
43	-9	57	12	Right Posterior Cingulate
22	42	-12	27	Left Middle Frontal Gyrus
20	36	-48	18	Left Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S22: Coordinates associated to metacognition task of multiplication level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
68	42	-12	27	Left Middle Frontal Gyrus
44	-6	57	15	Right Posterior Cingulate
37	51	54	-6	Left Inferior Temporal Gyrus
11	6	-9	-6	Left Caudate

11 57 15 36 Left Precentral Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S23: Coordinates associated to metacognition task of multiplication level 2 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
76	42	-9	36	Left Middle Frontal Gyrus
32	57	51	-9	Left Middle Temporal Gyrus
18	42	30	51	Left Postcentral Gyrus
16	-30	-48	36	Right Superior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S24: Coordinates associated to metacognition task of multiplication level 3 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
53	30	-18	33	Left Middle Frontal Gyrus
20	15	-12	-3	Left Lentiform Nucleus
18	48	-33	24	Left Middle Frontal Gyrus
15	-12	-18	6	Right Caudate
13	0	-60	15	Left Medial Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S25: Coordinates associated to metacognition task of division level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
58	42	-21	36	Left Precentral Gyrus
31	54	54	-9	Left Middle Temporal Gyrus
18	-6	57	15	Right Posterior Cingulate
12	-21	48	33	Right Precuneus
10	36	-51	18	Left Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S26: Coordinates associated to metacognition task of division level 2 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
48	9	-12	6	Left Caudate
37	39	-3	24	Left Precentral Gyrus
35	-15	-15	-9	Right Lentiform Nucleus
27	-12	57	12	Right Posterior Cingulate
12	63	45	18	Left Superior Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S27: Coordinates associated to metacognition task of division level 3 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
26	60	51	-9	Left Inferior Temporal Gyrus
24	6	-9	-6	Left Caudate
15	6	48	9	Left Posterior Cingulate
15	-54	66	42	Right Inferior Parietal Lobule
11	-9	-6	9	Right Caudate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space

with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S28: Coordinates associated to metacognition task of control level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
34	12	-18	3	Left Caudate
11	27	-18	36	Left Middle Frontal Gyrus
10	18	24	72	Left Precentral Gyrus
9	-48	24	60	Right Postcentral Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S29: Coordinates associated to metacognition task of control level 2 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
32	3	72	18	Left Cuneus
26	42	-12	24	Left Inferior Frontal Gyrus
18	33	78	39	Left Precuneus
15	-6	57	15	Right Posterior Cingulate
13	54	48	-6	Left Middle Temporal Gyrus
10	48	-24	42	Left Middle Frontal Gyrus
10	-18	-21	39	Right Cingulate Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S30: Coordinates associated to metacognition task of control level 3 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
21	39	-12	27	Left Middle Frontal Gyrus
19	18	-12	-6	Left Lentiform Nucleus

11	-12	60	12	Right Posterior Cingulate
11	54	-18	27	Left Middle Frontal Gyrus
10	54	54	-12	Left Inferior Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Metacognition tasks vs mathematical operation of addition level 1.

Table S31: Coordinates associated to metacognition task of addition level 1 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
8	57	9	-27	Left Inferior Temporal Gyrus
5	-27	69	33	Right Precuneus
5	-33	48	-30	Right Cerebellar Tonsil
5	18	84	-15	Left Lingual Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S32: Coordinates associated to metacognition task of addition level 2 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
7	42	15	42	Left Precentral Gyrus
5	51	-18	33	Left Middle Frontal Gyrus
4	9	51	-30	Left Nodule
4	-18	-3	15	Right Caudate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S33: Coordinates associated to metacognition task of addition level 3 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
16	-45	-33	9	Right Inferior Frontal Gyrus
16	-18	-15	15	Right Caudate
9	-24	-27	3	Right Claustrum
8	18	84	-18	Left Declive

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S34: Coordinates associated to metacognition task of subtraction level 1 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
17	-45	-39	-15	Right Inferior Frontal Gyrus
14	-27	27	27	Right Insula
13	66	36	-21	Left Inferior Temporal Gyrus
11	63	51	27	Left Supramarginal Gyrus
10	-69	27	-6	Right Middle Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S35: Coordinates associated to metacognition task of subtraction level 2 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
8	-39	21	39	Right Postcentral Gyrus
5	-42	-18	-30	Right Superior Temporal Gyrus
5	-42	-33	15	Right Middle Frontal Gyrus
5	-48	-15	18	Right Inferior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space

with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S36: Coordinates associated to metacognition task of subtraction level 3 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
41	15	90	3	Left Cuneus
29	-12	-12	3	Right Caudate
21	18	84	-15	Left Lingual Gyrus
17	-9	81	0	Right Lingual Gyrus
16	24	75	-30	Left Pyramis
14	-6	45	63	Right Postcentral Gyrus
13	-21	87	-12	Right Fusiform Gyrus
12	66	18	18	Left Postcentral Gyrus
12	-60	0	24	Right Precentral Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S37: Coordinates associated to metacognition task of multiplication level 1 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
17	-54	-18	15	Right Inferior Frontal Gyrus
7	57	24	-6	Left Middle Temporal Gyrus
7	9	30	27	Left Cingulate Gyrus
7	57	15	36	Left Precentral Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S38: Coordinates associated to metacognition task of multiplication level 2 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
--------	--------	--------	--------	-------------

10	-3	-42	-27	Right Orbital Gyrus
9	-57	30	-3	Right Middle Temporal Gyrus
9	48	27	-15	Left Middle Temporal Gyrus
6	30	48	48	Left Precuneus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S39: Coordinates associated to metacognition task of multiplication level 3 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
14	30	9	0	Left Lentiform Nucleus
6	-45	-36	-15	Left Middle Frontal Gyrus
6	21	27	15	Left Thalamus
4	-15	-3	-30	Right Uncus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S40: Coordinates associated to metacognition task of division level 1 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
15	-54	48	-42	Right Cerebellar Tonsil
12	-15	54	36	Right Precuneus
11	15	84	-15	Left Lingual Gyrus
10	-15	63	-48	Right Inferior Semi-Lunar Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S41: Coordinates associated to metacognition task of division level 2 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
9	-15	-15	-9	Right Lentiform Nucleus
8	-24	30	30	Right Cingulate Gyrus
7	-69	27	-9	Right Middle Temporal Gyrus
5	-24	24	-21	Right Parahippocampal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S42: Coordinates associated to metacognition task of division level 3 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
26	0	66	42	Right Precuneus
19	-12	-6	15	Right Caudate
17	-51	-3	-33	Right Middle Temporal Gyrus
14	9	39	-39	Left Cerebellar Tonsil
12	-54	-33	-15	Right Inferior Frontal Gyrus
12	-12	-51	42	Right Superior Frontal Gyrus
10	-60	54	42	Right Inferior Parietal Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S43: Coordinates associated to metacognition task of control level 1 vs mathematical operation of addition level 1

Voxels	Peak x	Peak y	Peak z	Brain label
15	-45	39	69	Right Postcentral Gyrus
15	57	57	42	Left Inferior Parietal Lobule
6	-63	15	15	Right Postcentral Gyrus
5	18	93	-27	Left Uvula

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space

with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S44: Coordinates associated to metacognition task of control level 2 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
23	18	90	-33	Left Pyramis
9	15	87	-18	Left Declive
8	-24	-15	36	Right Middle Frontal Gyrus
7	-21	-51	0	Right Superior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S45: Coordinates associated to metacognition task of control level 3 vs mathematical operation of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
12	45	27	-21	Left Fusiform Gyrus
9	-30	-3	-12	Right Superior Temporal Gyrus
8	-48	48	-45	Right Cerebellar Tonsil
8	-9	36	-42	Right Cerebellar Tonsil

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Metacognition tasks vs metacognition task of control level 1.

Table S46: Coordinates associated to metacognition task of addition level 1 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
29	3	57	51	Left Precuneus
16	12	-12	-24	Left Rectal Gyrus
9	39	-15	3	Left Insula

7 -48 -30 -15 Right Inferior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S47: Coordinates associated to metacognition task of addition level 2 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
30	-48	27	60	Right Postcentral Gyrus
13	18	-30	-18	Left Middle Frontal Gyrus
12	-42	42	63	Right Postcentral Gyrus
11	27	-15	42	Left Middle Frontal Gyrus
10	-36	-60	0	Right Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S48: Coordinates associated to metacognition task of addition level 3 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
17	-57	-15	24	Right Inferior Frontal Gyrus
17	0	84	27	Left Cuneus
14	9	78	12	Left Cuneus
10	3	-9	6	Left Caudate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S49: Coordinates associated to metacognition task of subtraction level 1 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
--------	--------	--------	--------	-------------

50	48	-12	0	Left Insula
36	-51	24	21	Right Postcentral Gyrus
26	-3	-21	51	Right Superior Frontal Gyrus
24	39	-21	3	Left Inferior Frontal Gyrus
23	51	-15	39	Left Middle Frontal Gyrus
22	42	-48	9	Left Middle Frontal Gyrus
17	27	-3	3	Left Lentiform Nucleus
16	30	78	27	Left Superior Occipital Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S50: Coordinates associated to metacognition task of subtraction level 2 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
12	-42	39	66	Right Postcentral Gyrus
8	-54	39	57	Right Inferior Parietal Lobule
7	-42	15	18	Right Insula
6	-9	-36	-6	Right Anterior Cingulate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S51: Coordinates associated to metacognition task of subtraction level 3 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
84	33	72	18	Left Middle Temporal Gyrus
45	27	69	48	Left Precuneus
42	-39	81	0	Right Middle Occipital Gyrus
29	3	87	27	Left Cuneus
29	-33	18	21	Right Insula
25	-48	24	60	Right Postcentral Gyrus
24	-6	30	66	Right Paracentral Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S52: Coordinates associated to metacognition task of multiplication level 1 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
26	0	81	18	Left Cuneus
16	-48	-24	-6	Right Inferior Frontal Gyrus
14	9	-18	-24	Left Rectal Gyrus
12	-51	24	21	Right Postcentral Gyrus
11	-57	-24	15	Right Inferior Frontal Gyrus
11	42	15	66	Left Precentral Gyrus
10	33	72	18	Left Middle Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S53: Coordinates associated to metacognition task of multiplication level 2 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
12	33	72	18	Left Middle Temporal Gyrus
12	27	57	30	Left Precuneus
8	-39	78	36	Right Precuneus
7	-24	-39	39	Right Superior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S54: Coordinates associated to metacognition task of multiplication level 3 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
--------	--------	--------	--------	-------------

14	-60	39	54	Right Inferior Parietal Lobule
13	3	-24	54	Left Superior Frontal Gyrus
10	-36	-60	9	Right Middle Frontal Gyrus
10	27	60	33	Left Precuneus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S55: Coordinates associated to metacognition task of division level 1 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
34	-39	78	36	Right Precuneus
18	42	-30	33	Left Middle Frontal Gyrus
12	54	-24	-6	Left Inferior Frontal Gyrus
12	-36	33	60	Right Postcentral Gyrus
11	21	96	15	Left Middle Occipital Gyrus
10	39	51	-24	Left Culmen
10	30	78	24	Left Superior Occipital Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S56: Coordinates associated to metacognition task of division level 2 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
26	27	72	30	Left Cuneus
14	24	51	66	Left Postcentral Gyrus
8	33	-42	6	Left Middle Frontal Gyrus
8	42	57	30	Left Angular Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S57: Coordinates associated to metacognition task of division level 3 vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
28	-42	-21	-12	Right Inferior Frontal Gyrus
21	-51	36	-39	Right Cerebellar Tonsil
10	6	78	54	Left Precuneus
9	-48	15	15	Right Insula

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Full-scale brain coordinates of mathematical cognition.

Mathematical cognition tasks vs fixation

Table S58: Coordinates associated to mathematical task of addition level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
10813	-6	84	45	Right Precuneus
3007	57	-18	-3	Left Inferior Frontal Gyrus
1237	39	81	-15	Left Declive
854	-39	90	-9	Right Inferior Occipital Gyrus
281	3	-6	60	Left Superior Frontal Gyrus
181	-6	-18	6	Right Caudate
180	54	-9	45	Left Middle Frontal Gyrus
102	45	63	-48	Left Cerebellar Tonsil
89	-30	6	51	Right Precentral Gyrus
31	-6	-30	-33	Right Orbital Gyrus
30	-9	72	-21	Right Declive
29	0	45	-36	Left Cerebellar Tonsil
26	-42	-9	33	Right Inferior FrontalGyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S59: Coordinates associated to mathematical task of addition level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
4706	-3	81	48	Right Precuneus
2468	54	60	45	Left Inferior Parietal Lobule
1355	33	93	-15	Left Inferior Occipital Gyrus
660	-18	93	-18	Right Fusiform Gyrus
601	51	-3	51	Left Precentral Gyrus
317	-27	72	60	Right Superior Parietal Lobule
260	-21	-15	0	Right Lentiform Nucleus
141	24	-57	36	Left Superior Frontal Gyrus
137	45	-15	48	Left Middle Frontal Gyrus
101	-30	6	51	Right Precentral Gyrus
87	-6	78	-39	Right Inferior Semi-Lunar
45	3	30	-3	Left Thalamus
42	-39	15	42	Right Precentral Gyrus
40	48	72	-30	Left Tuber
32	-42	-9	33	Right Inferior Frontal Gyrus
30	21	90	-33	Left Pyramis
28	3	48	-33	Left Cerebellar Tonsil

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S60: Coordinates associated to mathematical task of addition level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
3673	0	87	42	Left Cuneus
2414	-54	-27	-9	Right Inferior Frontal Gyrus
1600	45	66	51	Left Inferior Parietal Lobule
1263	27	99	-6	Left Lingual Gyrus
608	-36	96	-6	Right Inferior Occipital Gyrus
310	-24	72	57	Right Superior Parietal Lobule
288	51	-6	48	Left Middle Frontal Gyrus
250	3	-6	60	Left Superior Frontal Gyrus

211	-39	-27	54	Right Superior Frontal Gyrus
130	36	-24	57	Left Middle Frontal Gyrus
117	24	-60	33	Left Superior Frontal Gyrus
114	-30	6	51	Right Precentral Gyrus
67	-6	-21	3	Right Caudate
36	-42	15	42	Right Precentral Gyrus
28	0	45	-36	Left Cerebellar Tonsil
25	-42	-9	33	Right Inferior Frontal Gyrus
24	30	-12	-24	Left Superior Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S61: Coordinates associated to mathematical task of subtraction level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
5125	-3	84	48	Right Precuneus
2280	54	-21	-6	Left Inferior Frontal Gyrus
1176	39	78	-18	Left Declive
634	-45	90	0	Right Middle Occipital Gyrus
610	54	-9	45	Left Middle Frontal Gyrus
233	-27	72	60	Right Superior Parietal Lobule
147	-6	-18	6	Right Caudate
123	-30	6	51	Right Precentral Gyrus
46	0	45	-36	Left Cerebellar Tonsil
32	-6	78	-42	Right Inferior Semi-Lunar Lobule
32	15	-9	9	Left Caudate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S62: Coordinates associated to mathematical task of subtraction level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
1836	-51	57	57	Right Inferior Parietal Lobule

1537	30	87	-18	Left Declive
1531	0	84	48	Left Precuneus
1409	54	-24	-6	Left Inferior Frontal Gyrus
842	-39	90	-9	Right Inferior Occipital Gyrus
615	51	-6	48	Left Middle Frontal Gyrus
420	0	-69	18	Left Medial Frontal Gyrus
345	-27	72	60	Right Superior Parietal Lobule
324	-60	-24	-3	Right Inferior Frontal Gyrus
162	-27	3	54	Right Middle Frontal Gyrus
135	-6	-21	6	Right Caudate
128	-36	-27	57	Right Superior Frontal Gyrus
105	15	69	-9	Left Declive
95	15	-30	3	Left Anterior Cingulate
74	36	-30	51	Left Superior Frontal Gyrus
62	15	-66	30	Left Superior Frontal Gyrus
59	-42	-9	33	Right Inferior Frontal Gyrus
48	0	27	-3	Posterior Commissure
31	-66	-9	9	Right Precentral Gyrus
28	-12	-39	60	Right Superior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S63: Coordinates associated to mathematical task of subtraction level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
2100	-60	-21	0	Right Inferior Frontal Gyrus
1592	54	63	42	Left Inferior Parietal Lobule
1514	0	87	42	Left Cuneus
1436	33	93	-12	Left Inferior Occipital Gyrus
1244	21	-60	33	Left Superior Frontal Gyrus
953	-42	90	-12	Right Inferior Occipital Gyrus
443	42	-12	36	Left Middle Frontal Gyrus
220	-12	39	-6	Right Culmen
98	-30	3	51	Right Middle Frontal Gyrus

79	9	42	0	Left Parahippocampal Gyrus
62	18	51	72	Left Postcentral Gyrus
61	15	-12	9	Left Caudate
44	-45	-9	36	Right Middle Frontal Gyrus
36	3	75	-3	Left Lingual Gyrus
35	-57	6	-36	Right Inferior Temporal Gyrus
29	21	27	-3	Left Thalamus
25	57	-24	12	Left Inferior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S64: Coordinates associated to mathematical task of multiplication level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
9908	0	84	45	Right Precuneus
2351	54	-21	-6	Left Inferior Frontal Gyrus
849	24	93	3	Left Middle Occipital Gyrus
559	-39	90	-9	Right Inferior Occipital Gyrus
356	24	-57	36	Left Superior Frontal Gyrus
160	51	-6	48	Left Middle Frontal Gyrus
156	30	0	69	Left Superior Frontal Gyrus
131	-27	72	60	Right Superior Parietal Lobule
77	3	-6	60	Left Superior Frontal Gyrus
54	9	-24	6	Left Caudate
54	54	3	-39	Left Inferior Temporal Gyrus
49	51	57	-45	Left Cerebellar Tonsil
46	-30	6	51	Right Precentral Gyrus
43	-6	-21	6	Right Caudate
34	0	36	0	Right Culmen
30	39	15	39	Left Precentral Gyrus
28	42	-48	27	Left Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space

with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S65: Coordinates associated to mathematical task of multiplication level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
5107	-6	81	51	Right Precuneus
2301	54	-21	-6	Left Inferior Frontal Gyrus
1189	30	78	-21	Left Declive
668	51	-3	51	Left Precentral Gyrus
541	-36	93	-9	Right Inferior Occipital Gyrus
431	-21	-15	0	Right Lentiform Nucleus
272	-24	69	57	Right Superior Parietal Lobule
157	9	45	0	Left Culmen
151	36	-27	54	Left Superior Frontal Gyrus
99	-6	78	-42	Right Inferior Semi-Lunar Lobule
78	3	48	-36	Left Cerebellar Tonsil
69	-30	6	51	Right Precentral Gyrus
37	-33	57	-27	Right Tuber
33	24	27	-3	Left Thalamus
29	3	33	-3	Left Culmen
29	-39	-6	33	Right Inferior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S66: Coordinates associated to mathematical task of multiplication level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
1581	33	96	-9	Left Inferior Occipital Gyrus
1462	51	-3	51	Left Precentral Gyrus
915	-24	90	-18	Right Fusiform Gyrus
690	-51	57	57	Right Inferior Parietal Lobule
470	57	57	39	Left Inferior Parietal Lobule
463	-6	84	45	Right Precuneus

399	-27	72	60	Right Superior Parietal Lobule
324	0	15	66	Left Medial Frontal Gyrus
205	-18	69	-12	Right Declive
191	-42	-3	-6	Right Insula
171	39	12	3	Left Insula
127	-27	6	51	Right Middle Frontal Gyrus
79	0	24	-6	Posterior Commissure
62	0	12	15	Left Thalamus
51	3	48	-36	Left Cerebellar Tonsil
51	9	42	-3	Left Culmen
51	0	-24	24	Left Anterior Cingulate
47	-42	-9	33	Right Inferior Frontal Gyrus
47	-57	-24	-6	Right Inferior Frontal Gyrus
37	54	36	30	Left Supramarginal Gyrus
34	21	24	-6	Left Parahippocampal Gyrus
33	-57	9	-12	Right Middle Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S67: Coordinates associated to mathematical task of division level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
10088	-6	81	51	Right Precuneus
2634	57	-18	-3	Left Inferior Frontal Gyrus
1120	33	96	-9	Left Inferior Occipital Gyrus
606	-39	90	-9	Right Inferior Occipital Gyrus
381	54	-9	45	Left Middle Frontal Gyrus
160	-27	72	60	Right Superior Parietal Lobule
107	3	-3	60	Left Medial Frontal Gyrus
89	-6	-21	6	Right Caudate
61	-30	6	51	Right Precentral Gyrus
48	-39	15	42	Right Precentral Gyrus
43	-3	33	0	Right Thalamus

39	15	-30	3	Left Anterior Cingulate
35	-42	-9	33	Right Inferior Frontal Gyrus
32	0	-39	-30	Left Orbital Gyrus
31	-51	45	-48	Right Cerebellar Tonsil
29	39	18	-36	Left Inferior Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S68: Coordinates associated to mathematical task of division level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
3715	-6	81	51	Right Precuneus
2702	-57	-21	-6	Right Inferior Frontal Gyrus
1693	57	-18	-3	Left Inferior Frontal Gyrus
1240	33	96	-9	Left Inferior Occipital Gyrus
557	-36	93	-9	Right Inferior Occipital Gyrus
341	54	-9	45	Left Middle Frontal Gyrus
263	27	-12	69	Left Superior Frontal Gyrus
204	-27	72	60	Right Superior Parietal Lobule
188	12	66	-9	Left Culmen
156	-39	-27	54	Right Superior Frontal Gyrus
70	-21	-12	-3	Right Lentiform Nucleus
63	15	-9	6	Left Lentiform Nucleus
54	-27	6	51	Right Middle Frontal Gyrus
54	-39	15	42	Right Precentral Gyrus
49	-3	72	-27	Right Pyramis of Vermis
39	0	51	-39	Right Cerebellar Tonsil
29	12	-18	-30	Left Orbital Gyrus
28	-42	-9	33	Right Inferior Frontal Gyrus
25	21	-3	-21	Left Uncus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S69: Coordinates associated to mathematical task of division level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
2210	-60	-21	-3	Right Inferior Frontal Gyrus
1670	54	-27	-9	Left Inferior Frontal Gyrus
1072	24	99	12	Left Middle Occipital Gyrus
584	-18	63	-9	Right Culmen
568	0	87	39	Left Cuneus
532	-39	90	-9	Right Inferior Occipital Gyrus
242	45	-9	36	Left Middle Frontal Gyrus
226	-24	69	57	Right Superior Parietal Lobule
178	21	45	72	Left Postcentral Gyrus
132	-18	-63	33	Right Superior Frontal Gyrus
127	30	0	69	Left Superior Frontal Gyrus
117	18	-60	33	Left Superior Frontal Gyrus
90	-51	-12	54	Right Middle Frontal Gyrus
68	3	-6	60	Left Superior Frontal Gyrus
62	3	-33	60	Left Superior Frontal Gyrus
44	-45	-3	36	Right Precentral Gyrus
41	-30	3	48	Right Middle Frontal Gyrus
40	-3	33	0	Right Thalamus
35	-18	-15	3	Right Lentiform Nucleus
31	3	45	-36	Left Cerebellar Tonsil
31	33	-27	48	Left Superior Frontal Gyrus
28	18	-12	-6	Left Lentiform Nucleus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S70: Coordinates associated to font task of control level 1 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
8618	-3	84	48	Right Precuneus
2082	57	-18	-3	Left Inferior Frontal Gyrus
1182	39	81	-15	Left Declive

1056	-45	87	-12	Right Inferior Occipital Gyrus
278	54	-9	45	Left Middle Frontal Gyrus
95	3	-6	57	Left Superior Frontal Gyrus
76	-30	6	51	Right Precentral Gyrus
46	-45	-3	36	Right Precentral Gyrus
33	12	-27	3	Left Caudate
33	-6	-21	6	Right Caudate
27	0	45	-36	Left Cerebellar Tonsil

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S71: Coordinates associated to font task of control level 2 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
8900	0	84	45	Right Precuneus
2197	57	-18	-3	Left Inferior Frontal Gyrus
1337	39	81	-18	Left Declive
1150	-39	90	-9	Right Inferior Occipital Gyrus
330	54	-9	45	Left Middle Frontal Gyrus
96	3	-6	57	Left Superior Frontal Gyrus
92	-30	6	51	Right Precentral Gyrus
69	63	-6	12	Left Precentral Gyrus
63	-42	-9	33	Right Inferior Frontal Gyrus
57	-6	78	-42	Right Inferior Semi-Lunar Lobule
55	9	-24	3	Left Caudate
53	-6	-21	6	Right Caudate
32	-39	15	42	Right Precentral Gyrus
30	42	-48	21	Left Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S72: Coordinates associated to font task of control level 3 vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain label
8147	0	84	45	Right Precuneus
2357	57	-18	-3	Left Inferior Frontal Gyrus
1370	39	78	-18	Left Declive
1260	-39	90	-9	Right Inferior Occipital Gyrus
386	24	-57	36	Left Superior Frontal Gyrus
162	24	3	54	Left Middle Frontal Gyrus
143	54	-9	45	Left Middle Frontal Gyrus
104	-30	6	51	Right Precentral Gyrus
104	3	-3	60	Left Medial Frontal Gyrus
68	-42	-9	33	Right Inferior Frontal Gyrus
66	-6	-21	6	Right Caudate
55	-6	78	-42	Right Inferior Semi-Lunar Lobule
46	0	45	-36	Left Cerebellar Tonsil
44	15	-30	3	Left Anterior Cingulate
40	0	-39	-33	Right Orbital Gyrus
31	48	60	-48	Left Cerebellar Tonsil
27	42	-48	27	Left Middle Frontal Gyrus
26	21	87	-42	Left Inferior Semi-Lunar Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Mathematical tasks vs font control tasks

Table S73: Coordinates associated to mathematical task of addition level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
74	-54	75	-6	Right Middle Occipital Gyrus
64	33	48	-21	Left Culmen
56	-48	33	-24	Right Fusiform Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space

with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S74: Coordinates associated to mathematical task of addition level 2 vs the font task of control level 2.

Voxels	Peak x	Peak y	Peak z	Brain label
158	54	36	57	Left Inferior Parietal Lobule
153	24	78	54	Left Precuneus
152	-63	60	0	Right Middle Temporal Gyrus
109	3	-3	69	Left Superior Frontal Gyrus
105	51	-9	48	Left Middle Frontal Gyrus
77	-60	63	33	Right Supramarginal Gyrus
71	30	66	-18	Left Declive
71	54	60	45	Left Inferior Parietal Lobule
51	-51	-36	-15	Right Inferior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S75: Coordinates associated to mathematical task of addition level 3 vs the font task of control level 3.

Voxels	Peak x	Peak y	Peak z	Brain label
118	-24	72	-12	Right Declive
103	54	36	60	Left Inferior Parietal Lobule
70	21	-9	72	Left Superior Frontal Gyrus
68	30	69	60	Left Superior Parietal Lobule
62	-24	-12	72	Right Superior Frontal Gyrus
46	54	-15	36	Left Middle Frontal Gyrus
43	15	0	21	Left Caudate
36	-57	36	60	Right Inferior Parietal Lobule
36	45	63	30	Left Angular Gyrus
33	0	6	57	Left Medial Frontal Gyrus
30	-9	69	18	Right Precuneus
28	54	66	-12	Left Fusiform Gyrus

25	-21	-15	3	Right Lentiform Nucleus
24	15	78	-12	Left Declive

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S76: Coordinates associated to mathematical task of subtraction level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
179	-54	75	-9	Right Middle Occipital Gyrus
38	27	51	- 15	Left Culmen

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S77: Coordinates associated to mathematical task of subtraction level 2 vs the font task of control level 2.

Voxels	Peak x	Peak y	Peak z	Brain label
274	57	33	57	Left Postcentral Gyrus
112	54	-15	39	Left Middle Frontal Gyrus
101	27	-9	69	Left Superior Frontal Gyrus
96	-24	-6	72	Right Superior Frontal Gyrus
43	51	57	-9	Left Middle Temporal Gyrus
35	27	54	-12	Left Declive
33	-12	72	57	Right Superior Parietal Lobule
30	-42	15	-30	Right Inferior Temporal Gyrus
29	-18	60	-21	Right Culmen
25	39	-42	9	Left Middle Frontal Gyrus
24	-6	-30	-21	Right Rectal Gyrus
22	-21	-15	12	Right Caudate
22	48	-30	36	Left Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S78: Coordinates associated to mathematical task of subtraction level 3 vs the font task of control level 3.

Voxels	Peak x	Peak y	Peak z	Brain label
188	3	84	45	Left Precuneus
81	-36	36	-24	Right Culmen
76	24	-15	69	Left Superior Frontal Gyrus
61	39	-9	36	Left Middle Frontal Gyrus
57	-6	84	42	Right Precuneus
44	-27	-9	72	Right Superior Frontal Gyrus
31	-3	78	18	Right Cuneus
25	36	-57	24	Left Superior Frontal Gyrus
24	-39	54	-30	Right Culmen
19	60	60	-12	Left Inferior Temporal Gyrus
18	15	99	-9	Left Lingual Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S79: Coordinates associated to mathematical task of multiplication level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
212	-60	66	-3	Right Middle Occipital Gyrus
67	30	63	-18	Left Declive
60	-48	36	66	Right Postcentral Gyrus
56	-54	-21	42	Right Middle Frontal Gyrus
37	-66	15	36	Right Postcentral Gyrus
34	-51	-42	15	Right Middle Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space

with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S80: Coordinates associated to mathematical task of multiplication level 2 vs the font task of control level 2.

Voxels	Peak x	Peak y	Peak z	Brain label
270	51	-3	51	Left Precentral Gyrus
165	-57	69	3	Right Middle Occipital Gyrus
121	-45	69	-27	Right Tuber
115	48	-45	12	Left Inferior Frontal Gyrus
110	57	36	57	Left Postcentral Gyrus
109	-12	-3	21	Right Caudate
107	-42	9	66	Right Precentral Gyrus
93	33	57	51	Left Superior Parietal Lobule
58	57	63	27	Left Superior Temporal Gyrus
54	-21	96	27	Right Cuneus
45	-30	48	15	Right Superior Temporal Gyrus
37	21	0	9	Left Lentiform Nucleus
35	33	48	-24	Left Culmen
33	3	-3	69	Left Superior Frontal Gyrus
25	21	-3	51	Left Medial Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S81: Coordinates associated to mathematical task of multiplication level 3 vs the font task of control level 3.

Voxels	Peak x	Peak y	Peak z	Brain label
298	36	-63	15	Left Middle Frontal Gyrus
284	-39	-57	24	Right Superior Frontal Gyrus
120	0	27	27	Left Cingulate Gyrus
113	3	69	6	Left Cuneus
98	0	75	48	Left Precuneus

84	-27	-12	69	Right Superior Frontal Gyrus
72	0	63	57	Left Precuneus
70	-27	72	-24	Right Uvula
68	42	54	63	Left Superior Parietal Lobule
67	-3	90	36	Right Cuneus
52	57	66	-9	Left Middle Occipital Gyrus
36	21	24	-6	Left Parahippocampal Gyrus
34	63	42	24	Left Inferior Parietal Lobule
31	-51	48	-39	Right Cerebellar Tonsil
29	-51	69	-6	Right Middle Occipital Gyrus
28	-21	69	9	Right Cuneus
23	-9	51	-24	Right Fastigium
20	9	36	-15	Left Culmen

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S82: Coordinates associated to mathematical task of division level 1 vs the font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
98	-57	69	-3	Right Middle Occipital Gyrus
34	30	60	-18	Left Declive

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S83: Coordinates associated to mathematical task of division level 2 vs the font task of control level 2.

Voxels	Peak x	Peak y	Peak z	Brain label
443	54	-18	42	Left Middle Frontal Gyrus
290	51	39	63	Left Inferior Parietal Lobule
144	27	-12	69	Left Superior Frontal Gyrus

			160	
109	57	51	-24	Left Tuber
80	0	3	54	Left Medial Frontal Gyrus
50	6	-12	18	Left Caudate
50	6	-24	48	Left Superior Frontal Gyrus
46	-24	-18	69	Right Superior Frontal Gyrus
42	-21	-12	-6	Right Lentiform Nucleus
41	36	9	66	Left Precentral Gyrus
29	-42	15	60	Right Precentral Gyrus
25	-39	63	-15	Right Declive
25	-54	72	-3	Right Middle Occipital Gyrus
24	-9	81	-21	Right Declive
20	-27	93	27	Right Cuneus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S84: Coordinates associated to mathematical task of division level 3 vs the font task of control level 3.

Voxels	Peak x	Peak y	Peak z	Brain label
365	3	84	45	Left Precuneus
331	51	51	57	Left Inferior Parietal Lobule
245	-45	3	60	Right Middle Frontal Gyrus
168	-54	75	0	Right Middle Occipital Gyrus
114	42	-33	42	Left Middle Frontal Gyrus
109	33	60	-18	Left Declive
62	-30	-12	69	Right Middle Frontal Gyrus
61	27	-15	66	Left Middle Frontal Gyrus
46	0	-24	45	Left Medial Frontal Gyrus
34	42	-57	12	Left Middle Frontal Gyrus
33	-39	-48	39	Right Middle Frontal Gyrus
33	-3	3	51	Right Medial Frontal Gyrus
29	21	9	72	Left Superior Frontal Gyrus
26	-3	-42	21	Right Medial Frontal Gyrus
24	-3	-54	3	Right Medial Frontal Gyrus

22	60	21	39	Left Postcentral Gyrus
21	-48	60	57	Right Superior Parietal Lobule
20	48	-48	0	Left Inferior Frontal Gyrus
19	18	75	-12	Left Declive

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Mathematical tasks of the same operation

Table S85: Coordinates associated to mathematical task of addition level 2 vs mathematical task of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
124	-15	96	-18	Right Lingual Gyrus
58	57	-18	33	Left Middle Frontal Gyrus
58	45	45	48	Left Inferior Parietal Lobule
54	27	66	57	Left Superior Parietal Lobule
43	33	96	-9	Left Inferior Occipital Gyrus
37	0	9	57	Left Medial Frontal Gyrus
28	3	-9	57	Left Superior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S86: Coordinates associated to mathematical task of addition level 3 vs mathematical task of addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
195	-18	102	-12	Right Lingual Gyrus
110	27	99	-6	Left Lingual Gyrus
58	57	-18	33	Left Middle Frontal Gyrus
52	-24	-12	69	Right Superior Frontal Gyrus
41	54	63	-9	Left Middle Occipital Gyrus
30	12	66	9	Left Cuneus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S87: Coordinates associated to mathematical task of subtraction level 2 vs mathematical task of subtraction level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
156	24	102	-6	Left Lingual Gyrus
103	-24	102	0	Right Cuneus
96	51	57	-9	Left Middle Temporal Gyrus
77	48	42	60	Left Inferior Parietal Lobule
46	-27	-9	69	Right Superior Frontal Gyrus
41	54	-15	39	Left Middle Frontal Gyrus
28	18	69	60	Left Superior Parietal Lobule
24	-12	72	57	Right Superior Parietal Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S88: Coordinates associated to mathematical task of subtraction level 3 vs mathematical task of subtraction level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
218	-33	96	-6	Right Inferior Occipital Gyrus
157	24	102	-6	Left Lingual Gyrus
148	0	6	57	Left Medial Frontal Gyrus
79	-6	84	42	Right Precuneus
45	12	72	33	Left Cuneus
38	0	75	-24	Left Tuber of Vermis
38	-45	-9	36	Right Middle Frontal Gyrus
35	36	-60	18	Left Superior Frontal Gyrus
30	39	-9	36	Left Middle Frontal Gyrus
28	15	9	69	Left Superior Frontal Gyrus
27	51	60	-6	Left Middle Occipital Gyrus

25	9	87	45	Left Precuneus
23	-27	-6	60	Right Middle Frontal Gyrus
23	48	60	24	Left Middle Temporal Gyrus
22	21	27	0	Left Thalamus
20	-63	-15	30	Right Inferior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S89: Coordinates associated to mathematical task of multiplication level 2 vs mathematical task of multiplication level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
306	54	42	60	Left Inferior Parietal Lobule
160	51	0	51	Left Precentral Gyrus
125	-21	66	-42	Right Inferior Semi-Lunar Lobule
93	45	-48	12	Left Middle Frontal Gyrus
82	-36	96	-6	Right Inferior Occipital Gyrus
78	51	63	-9	Left Middle Occipital Gyrus
61	-24	-12	69	Right Superior Frontal Gyrus
59	-30	48	42	Right Inferior Parietal Lobule
41	48	81	9	Left Middle Occipital Gyrus
41	0	-15	57	Left Superior Frontal Gyrus
36	-24	72	60	Right Superior Parietal Lobule
33	24	102	0	Left Cuneus
30	36	63	-24	Left Tuber
30	-24	51	12	Right Posterior Cingulate
30	-54	-36	33	Right Middle Frontal Gyrus
28	30	75	-21	Left Declive
25	30	-21	3	Left Insula
24	-9	48	-33	Right Cerebellar Tonsil
24	24	69	0	Left Lingual Gyrus
23	-21	-15	12	Right Caudate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space

with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S90: Coordinates associated to mathematical task of multiplication level 3 vs mathematical task of multiplication level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
1128	-27	-12	69	Right Superior Frontal Gyrus
467	33	93	-15	Left Inferior Occipital Gyrus
360	36	-63	15	Left Middle Frontal Gyrus
263	45	-12	36	Left Middle Frontal Gyrus
203	-24	90	-21	Right Uvula
173	0	6	12	Left Thalamus
141	51	66	-24	Left Tuber
126	-54	63	-24	Right Tuber
102	-48	-21	-6	Right Inferior Frontal Gyrus
89	-51	9	30	Right Precentral Gyrus
88	-45	72	-45	Right Inferior Semi-Lunar Lobule
70	54	6	27	Left Precentral Gyrus
59	0	39	21	Left Posterior Cingulate
56	-24	63	-21	Right Declive
56	-66	0	12	Right Precentral Gyrus
49	15	57	-6	Left Culmen
45	-33	87	33	Right Cuneus
35	21	27	-9	Left Parahippocampal Gyrus
32	-15	30	-9	Right Culmen
30	-21	54	3	Right Lingual Gyrus
29	-30	-60	-3	Right Superior Frontal Gyrus
26	57	-18	0	Left Inferior Frontal Gyrus
24	39	27	-30	Left Fusiform Gyrus
24	-24	18	-27	Right Parahippocampal Gyrus
24	15	0	24	Left Cingulate Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S91: Coordinates associated to mathematical task of division level 2 vs mathematical task of division level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
136	54	-18	39	Left Middle Frontal Gyrus
123	15	102	-12	Left Lingual Gyrus
104	54	45	-21	Left Tuber
93	-36	93	-6	Right Inferior Occipital Gyrus
78	-45	-36	45	Right Middle Frontal Gyrus
65	24	-18	66	Left Superior Frontal Gyrus
54	39	-60	9	Left Middle Frontal Gyrus
48	-24	-18	69	Right Superior Frontal Gyrus
43	6	57	0	Left Culmen
39	-57	48	-15	Right Fusiform Gyrus
37	-6	6	60	Right Medial Frontal Gyrus
32	-3	54	-42	Right Cerebellar Tonsil
30	0	-27	48	Left Superior Frontal Gyrus
25	3	6	57	Left Medial Frontal Gyrus
24	21	69	39	Left Precuneus
24	12	75	60	Left Superior Parietal Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S92: Coordinates associated to mathematical task of division level 3 vs mathematical task of division level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
183	-6	78	51	Right Precuneus
46	-3	51	45	Right Precuneus
27	-27	-9	63	Right Middle Frontal Gyrus
26	24	96	-12	Left Fusiform Gyrus
26	48	60	54	Left Inferior Parietal Lobule
22	-30	63	48	Right Superior Parietal Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S93: Coordinates associated to the font task of control level 2 vs font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
164	33	93	-15	Left Inferior Occipital Gyrus
123	-9	102	-9	Right Lingual Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S94: Coordinates associated to the font task of control level 3 vs font task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain label
507	-24	90	-15	Right Fusiform Gyrus
356	30	93	18	Left Fusiform Gyrus
38	-48	-12	3	Right Middle Frontal Gyrus
27	-54	48	7	Right Inferior Parietal Lobule
25	-27	81	5	Right Precuneus
22	-51	60	4	Right Inferior Parietal Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster-defining primary threshold of $p < 0.001$ cluster corrected. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Brain coordinates of metacognition

Figures S1-S5 show clusters that survived the contrast in several conditions. Tables S95-S102 summarize the results of whole-brain analyses.

Figure S1: Axial, coronal and sagittal view of clusters surviving the contrast metacognition task of addition vs fixation.

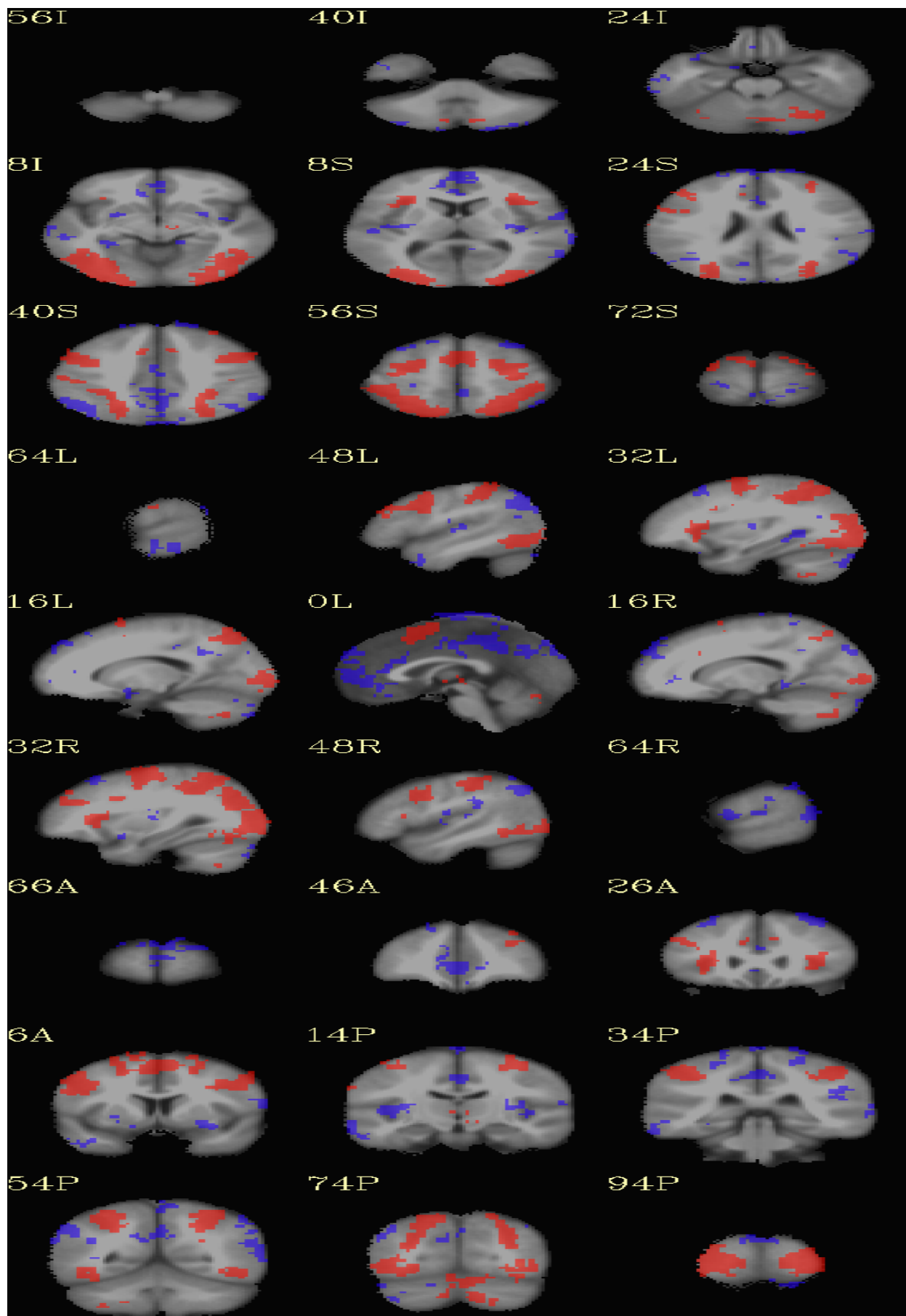


Figure S2: Sagittal view of clusters surviving the contrast metacognition task of control level 1 vs fixation.

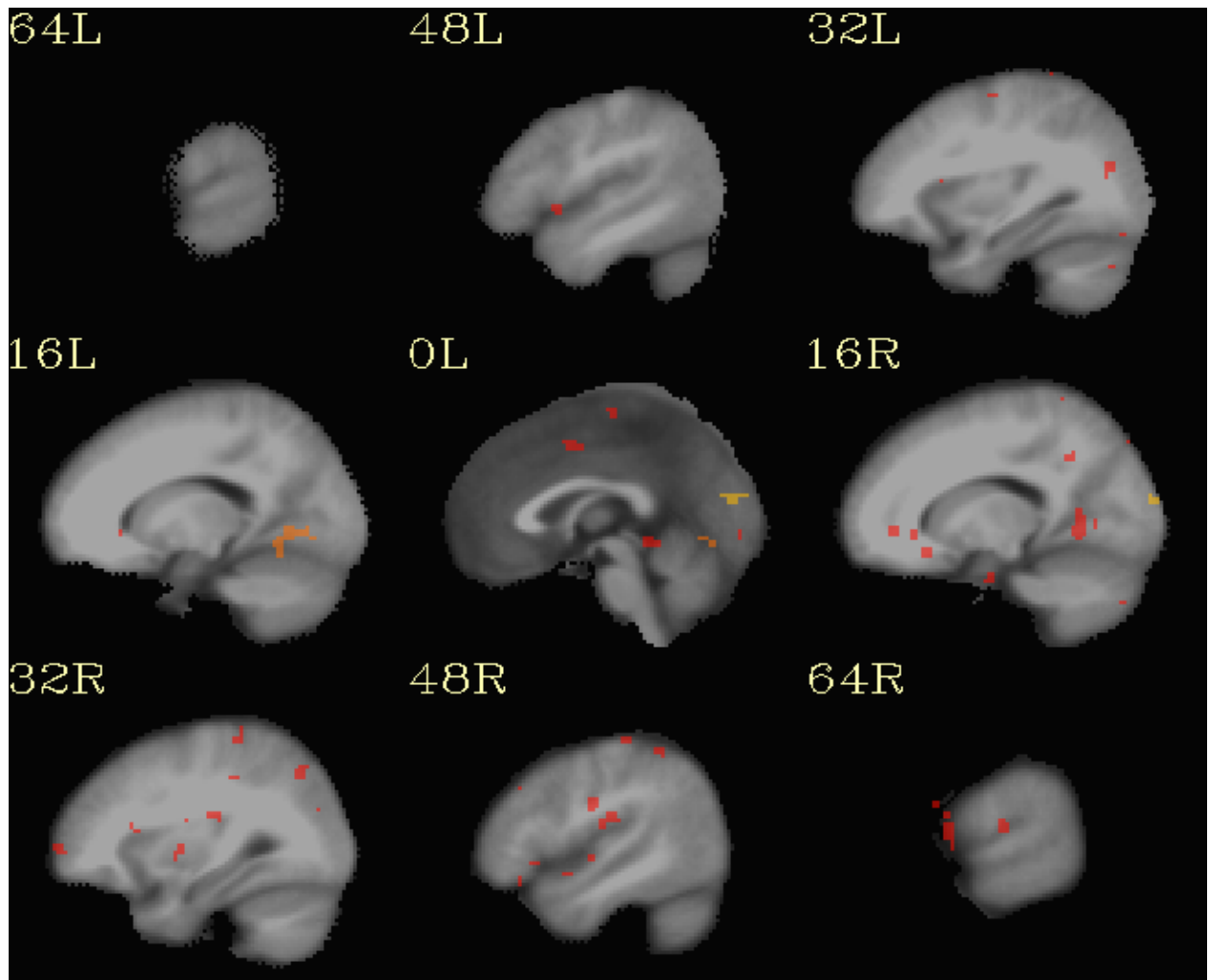


Table S95: Coordinates of the contrast metacognition tasks vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain area
80	6	81	12	Left Cuneus
72	12	60	-3	Left Culmen
64	-51	21	21	Right Postcentral Gyrus
58	-60	-15	15	Right Inferior Frontal Gyrus
45	-24	63	-15	Right Declive
27	-27	-6	12	Right Lentiform Nucleus
27	3	-3	48	Left Medial Frontal Gyrus
26	48	66	42	Left Inferior Parietal Lobule
26	-54	15	18	Right Postcentral Gyrus
26	12	75	-12	Left Declive
25	-51	-21	-6	Right Inferior Frontal Gyrus

25	-6	90	-3	Right Lingual Gyrus
24	-45	-36	-3	Right Middle Frontal Gyrus
24	-6	48	-33	Right Cerebellar Tonsil
24	-27	-18	9	Right Claustrum
23	-6	90	33	Right Cuneus
22	51	54	48	Left Inferior Parietal Lobule
22	48	21	42	Left Postcentral Gyrus
20	-51	15	33	Right Postcentral Gyrus
20	-45	12	30	Right Precentral Gyrus
20	36	-21	3	Left Insula
18	-24	45	66	Right Postcentral Gyrus
17	3	-48	24	Left Medial Frontal Gyrus
16	15	57	-15	Left Declive
15	9	-51	0	Left Medial Frontal Gyrus
14	57	48	12	Left Superior Temporal Gyrus
14	39	75	24	Left Middle Temporal Gyrus
14	-24	63	-21	Right Declive
14	-51	18	42	Right Postcentral Gyrus
14	48	-3	12	Left Precentral Gyrus
14	-21	-27	-3	Right Inferior Frontal Gyrus
14	-6	90	18	Right Cuneus
13	-42	-24	18	Right Middle Frontal Gyrus
13	15	-48	36	Left Superior Frontal Gyrus
13	9	-12	-30	Left Rectal Gyrus
13	-51	39	-42	Right Cerebellar Tonsil
13	-33	63	15	Right Middle Temporal Gyrus
12	-6	-63	21	Right Superior Frontal Gyrus
12	-36	84	0	Right Middle Occipital Gyrus
12	-12	-12	12	Right Caudate
12	-39	87	12	Right Middle Occipital Gyrus
12	24	12	51	Left Precentral Gyrus
12	-9	90	-24	Right Uvula
12	-42	69	12	Right Middle Temporal Gyrus
12	60	12	33	Left Precentral Gyrus
12	36	-18	12	Left Insula

			170	
12	-27	18	42	Right Middle Frontal Gyrus
12	0	-15	-3	Right Anterior Cingulate
11	-63	54	30	Right Supramarginal Gyrus
11	33	33	-3	Left Caudate
11	-63	39	-24	Right Inferior Temporal Gyrus
11	-36	69	12	Right Middle Occipital Gyrus
10	-60	6	33	Right Precentral Gyrus
10	-48	60	51	Right Inferior Parietal Lobule

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Figure S3: Sagittal view of clusters surviving the contrast metacognition task of subtraction level 1 vs font control task level 1.

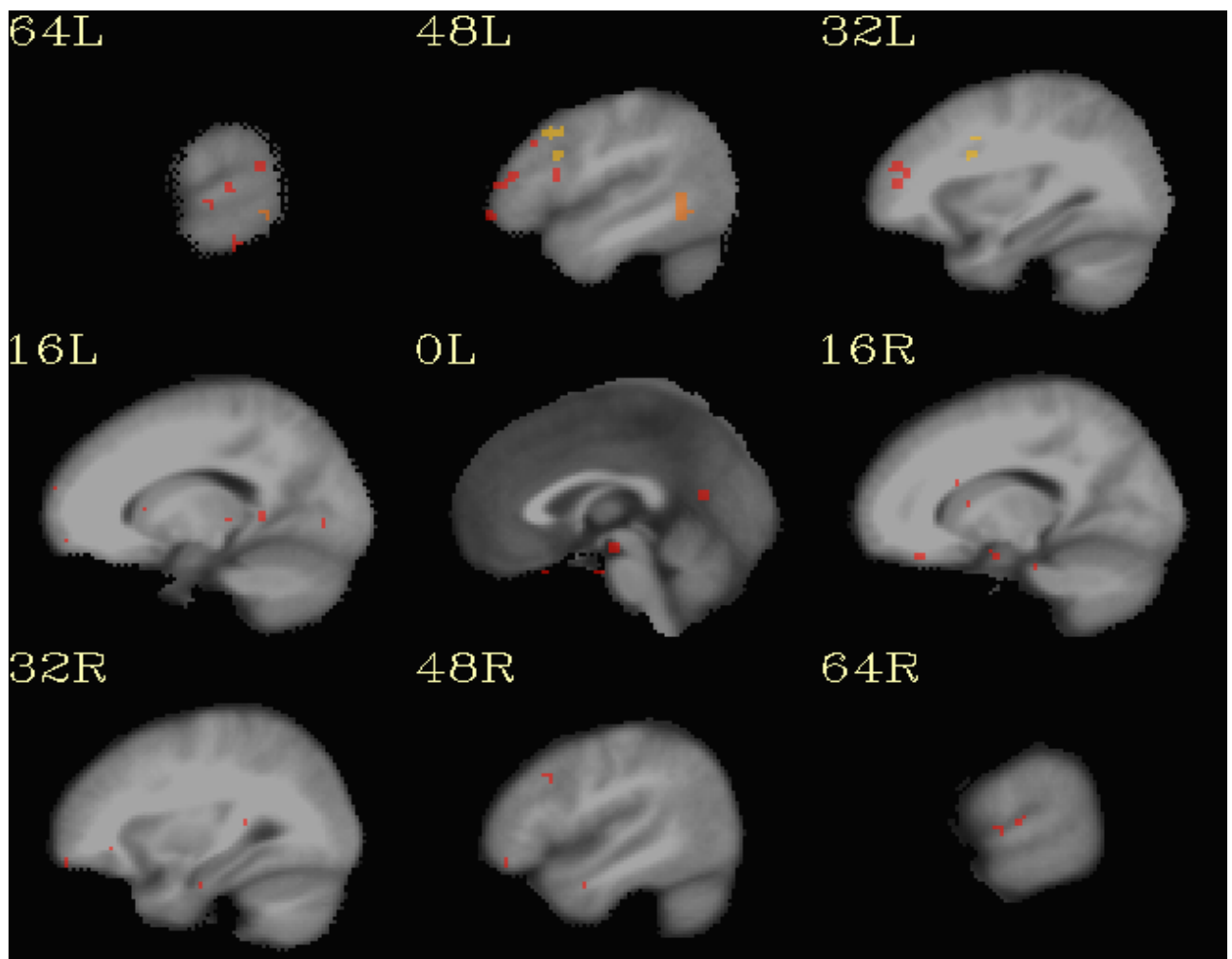


Table S96: Coordinates of the contrast metacognition tasks vs font control task level 1.

Voxels	Peak x	Peak y	Peak z	Brain area
85	42	-12	27	Left Middle Frontal Gyrus
76	42	-9	36	Left Middle Frontal Gyrus
68	57	48	-6	Left Middle Temporal Gyrus
68	42	-12	27	Left Middle Frontal Gyrus
67	51	54	-6	Left Inferior Temporal Gyrus
58	42	-21	36	Left Precentral Gyrus
53	30	-18	33	Left Middle Frontal Gyrus
48	9	-12	6	Left Caudate
44	-6	57	15	Right Posterior Cingulate
43	-9	57	12	Right Posterior Cingulate
39	-24	-3	9	Right Lentiform Nucleus
38	39	-9	33	Left Middle Frontal Gyrus
37	51	54	-6	Left Inferior Temporal Gyrus
37	39	-3	24	Left Precentral Gyrus
35	-15	-15	-9	Right Lentiform Nucleus
34	12	-18	3	Left Caudate
32	57	51	-9	Left Middle Temporal Gyrus
32	3	72	18	Left Cuneus
31	54	54	-9	Left Middle Temporal Gyrus
28	9	-6	12	Left Caudate
28	36	-42	9	Left Middle Frontal Gyrus
27	-12	57	12	Right Posterior Cingulate
26	60	51	-9	Left Inferior Temporal Gyrus
26	42	-12	24	Left Inferior Frontal Gyrus
25	42	-9	27	Left Inferior Frontal Gyrus
24	6	-9	-6	Left Caudate
22	42	-12	27	Left Middle Frontal Gyrus
21	33	-48	18	Left Middle Frontal Gyrus
21	39	-12	27	Left Middle Frontal Gyrus
20	36	-48	18	Left Middle Frontal Gyrus
20	15	-12	-3	Left Lentiform Nucleus
19	18	-12	-6	Left Lentiform Nucleus
18	42	30	51	Left Postcentral Gyrus

18	48	-33	24	Left Middle Frontal Gyrus
18	-6	57	15	Right Posterior Cingulate
18	33	78	39	Left Precuneus
16	57	51	-9	Left Middle Temporal Gyrus
16	-30	-48	36	Right Superior Frontal Gyrus
15	-12	-18	6	Right Caudate
15	6	48	9	Left Posterior Cingulate
15	-54	66	42	Right Inferior Parietal Lobule
15	-6	57	15	Right Posterior Cingulate
14	36	-48	12	Left Middle Frontal Gyrus
13	45	-36	24	Left Middle Frontal Gyrus
13	0	-60	15	Left Medial Frontal Gyrus
13	54	48	-6	Left Middle Temporal Gyrus
12	6	39	6	Left Parahippocampal Gyrus
12	-21	48	33	Right Precuneus
12	63	45	18	Left Superior Temporal Gyrus
11	-12	-3	-12	Right Subcallosal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Figure S4: Coronal view of clusters surviving the contrast metacognition task of subtraction level 3 vs mathematical operation addition level 1.

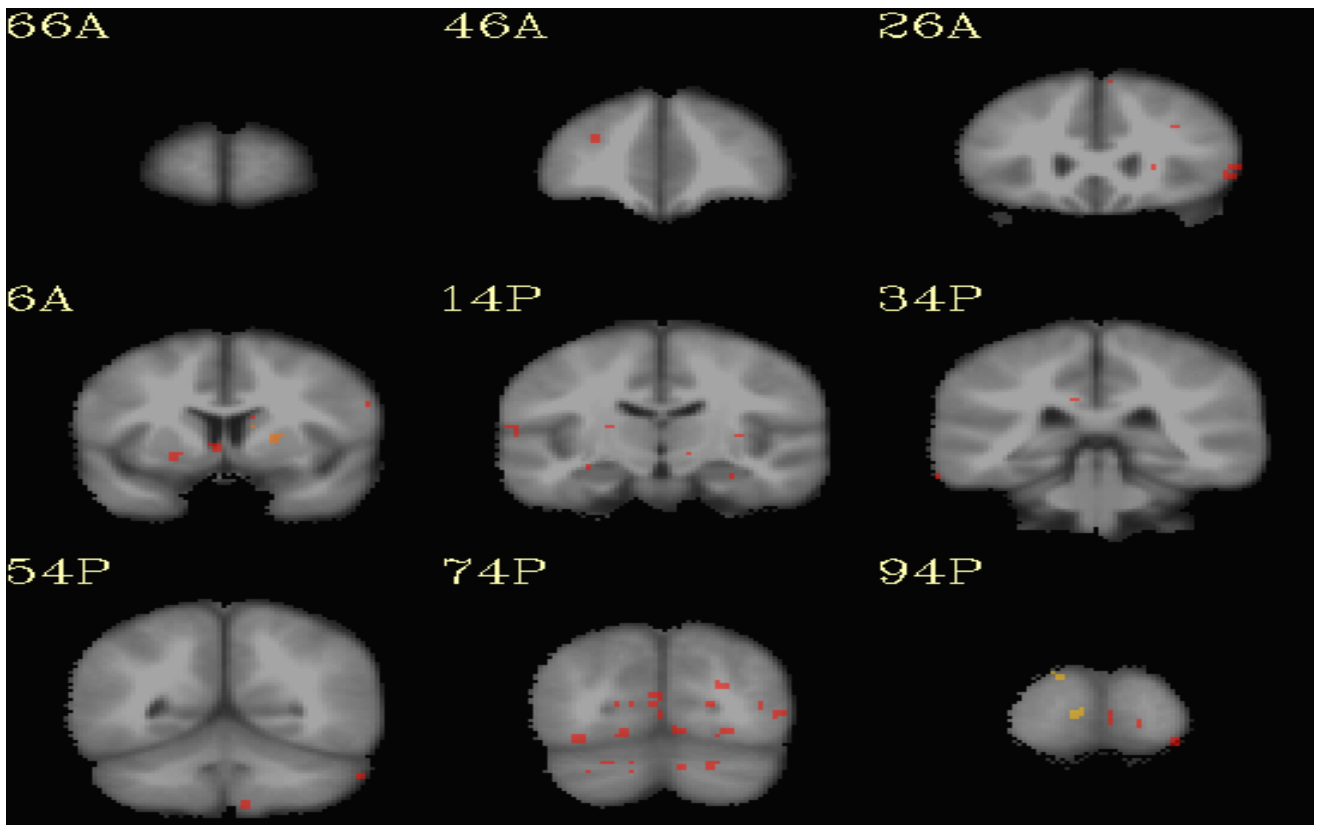


Table S97: Coordinates of the contrast metacognition tasks vs mathematical operation addition level 1.

Voxels	Peak x	Peak y	Peak z	Brain area
41	15	90	3	Left Cuneus
29	-12	-12	3	Right Caudate
26	0	66	42	Right Precuneus
23	18	90	-33	Left Pyramis
21	18	84	-15	Left Lingual Gyrus
19	-12	-6	15	Right Caudate
17	-45	-39	-15	Right Inferior Frontal Gyrus
17	-9	81	0	Right Lingual Gyrus
17	-54	-18	15	Right Inferior Frontal Gyrus
17	-51	-3	-33	Right Middle Temporal Gyrus
16	-45	-33	9	Right Inferior Frontal Gyrus
16	-18	-15	15	Right Caudate
16	24	75	-30	Left Pyramis
15	-54	48	-42	Right Cerebellar Tonsil
15	-45	39	69	Right Postcentral Gyrus
15	57	57	42	Left Inferior Parietal Lobule

14	-27	27	27	Right Insula
14	-6	45	63	Right Postcentral Gyrus
14	30	9	0	Left Lentiform Nucleus
14	9	39	-39	Left Cerebellar Tonsil
13	66	36	-21	Left Inferior Temporal Gyrus
13	-21	87	-12	Right Fusiform Gyrus
12	66	18	18	Left Postcentral Gyrus
12	-60	0	24	Right Precentral Gyrus
12	-15	54	36	Right Precuneus
12	-54	-33	-15	Right Inferior Frontal Gyrus
12	-12	-51	42	Right Superior Frontal Gyrus
12	45	27	-21	Left Fusiform Gyrus
11	63	51	27	Left Supramarginal Gyrus
11	15	84	-15	Left Lingual Gyrus
10	-69	27	-6	Right Middle Temporal Gyrus
10	-3	-42	-27	Right Orbital Gyrus
10	-15	63	-48	Right Inferior Semi-Lunar
10	-60	54	42	Right Inferior Parietal Lobule
9	-24	-27	3	Right Claustrum

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Figure S5: Coronal view of clusters surviving the contrast metacognition task of division level 1 vs metacognition task of control level 1.

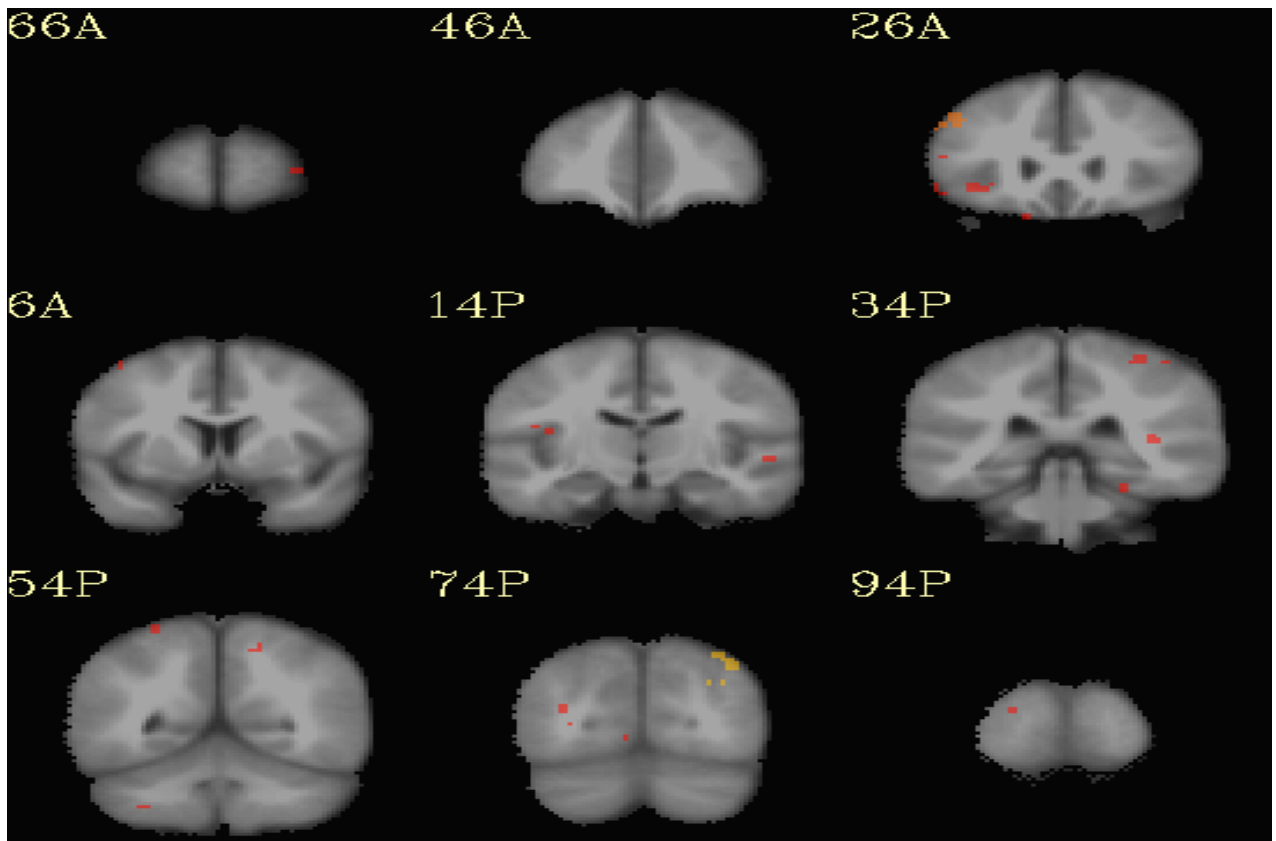


Table S98: Coordinates of the contrast metacognition tasks vs metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain area
84	33	72	18	Left Middle Temporal Gyrus
50	48	-12	0	Left Insula
45	27	69	48	Left Precuneus
42	-39	81	0	Right Middle Occipital Gyrus
36	-51	24	21	Right Postcentral Gyrus
34	-39	78	36	Right Precuneus
30	-48	27	60	Right Postcentral Gyrus
29	3	57	51	Left Precuneus
29	3	87	27	Left Cuneus
29	-33	18	21	Right Insula
28	-42	-21	-12	Right Inferior Frontal Gyrus
26	-3	-21	51	Right Superior Frontal Gyrus
26	0	81	18	Left Cuneus
26	27	72	30	Left Cuneus
25	-48	24	60	Right Postcentral Gyrus
24	39	-21	3	Left Inferior Frontal Gyrus

24	-6	30	66	Right Paracentral Lobule
23	51	-15	39	Left Middle Frontal Gyrus
22	42	-48	9	Left Middle Frontal Gyrus
21	-51	36	-39	Right Cerebellar Tonsil
18	42	-30	33	Left Middle Frontal Gyrus
17	-57	-15	24	Right Inferior Frontal Gyrus
17	0	84	27	Left Cuneus
17	27	-3	3	Left Lentiform Nucleus
16	12	-12	-24	Left Rectal Gyrus
16	30	78	27	Left Superior Occipital Gyrus
16	-48	-24	-6	Right Inferior Frontal Gyrus
14	9	78	12	Left Cuneus
14	9	-18	-24	Left Rectal Gyrus
14	-60	39	54	Right Inferior Parietal Lobule
14	24	51	66	Left Postcentral Gyrus
13	18	-30	-18	Left Middle Frontal Gyrus
13	3	-24	54	Left Superior Frontal Gyrus
12	-42	42	63	Right Postcentral Gyrus
12	-42	39	66	Right Postcentral Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S99: Coordinates of the contrast metacognition tasks of addition vs fixation, font control task, mathematical operation of addition level 1 and metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain area
39	-24	-3	9	Right Lentiform Nucleus
38	39	-9	33	Left Middle Frontal Gyrus
30	-48	27	60	Right Postcentral Gyrus
29	3	57	51	Left Precuneus
28	9	-6	12	Left Caudate
17	3	-48	24	Left Medial Frontal Gyrus
17	-57	-15	24	Right Inferior Frontal Gyrus
17	0	84	27	Left Cuneus

16	57	51	-9	Left Middle Temporal Gyrus
16	-45	-33	9	Right Inferior Frontal Gyrus
16	-18	-15	15	Right Caudate
16	12	-12	-24	Left Rectal Gyrus
14	36	-48	12	Left Middle Frontal Gyrus
14	9	78	12	Left Cuneus
13	-42	-24	18	Right Middle Frontal Gyrus
13	45	-36	24	Left Middle Frontal Gyrus
13	18	-30	-18	Left Middle Frontal Gyrus
12	-6	-63	21	Right Superior Frontal Gyrus
12	6	39	6	Left Parahippocampal Gyrus
12	-42	42	63	Right Postcentral Gyrus
11	27	-15	42	Left Middle Frontal Gyrus
10	-60	6	33	Right Precentral Gyrus
10	45	-45	12	Left Middle Frontal Gyrus
10	27	-9	39	Left Middle Frontal Gyrus
10	-36	-60	0	Right Middle Frontal Gyrus
10	3	-9	6	Left Caudate
9	54	21	-18	Left Inferior Temporal Gyrus
9	-42	42	21	Right Insula
9	18	66	-18	Left Declive
9	-48	48	24	Right Inferior Parietal Lobule
9	30	6	-21	Left Parahippocampal Gyrus
9	-24	-27	3	Right Claustrum
9	39	-15	3	Left Insula
8	-54	-9	48	Right Middle Frontal Gyrus
8	-27	-57	39	Right Superior Frontal Gyrus
8	57	9	-27	Left Inferior Temporal Gyrus
8	18	84	-18	Left Declive
7	9	66	-15	Left Declive
7	42	15	42	Left Precentral Gyrus
7	-48	-30	-15	Right Inferior Frontal Gyrus
6	27	-6	39	Left Middle Frontal Gyrus
5	-66	30	9	Right Superior Temporal Gyrus
5	24	-18	42	Left Middle Frontal Gyrus

5	45	15	-9	Left Superior Temporal Gyrus
5	-39	30	30	Right Inferior Parietal Lobule
5	-27	69	33	Right Precuneus
5	-33	48	-30	Right Cerebellar Tonsil
5	18	84	-15	Left Lingual Gyrus
5	51	-18	33	Left Middle Frontal Gyrus
4	9	51	-30	Left Nodule
4	-18	-3	15	Right Caudate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S100: Coordinates of the contrast metacognition task of subtraction vs fixation, font control task, mathematical operation of addition level 1 and metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain area
85	42	-12	27	Left Middle Frontal Gyrus
84	33	72	18	Left Middle Temporal Gyrus
68	57	48	-6	Left Middle Temporal Gyrus
67	51	54	-6	Left Inferior Temporal Gyrus
50	48	-12	0	Left Insula
45	27	69	48	Left Precuneus
43	-9	57	12	Right Posterior Cingulate
42	-39	81	0	Right Middle Occipital Gyrus
41	15	90	3	Left Cuneus
36	-51	24	21	Right Postcentral Gyrus
29	-12	-12	3	Right Caudate
29	3	87	27	Left Cuneus
29	-33	18	21	Right Insula
28	36	-42	9	Left Middle Frontal Gyrus
26	48	66	42	Left Inferior Parietal Lobule
26	-3	-21	51	Right Superior Frontal Gyrus
25	42	-9	27	Left Inferior Frontal Gyrus
25	-48	24	60	Right Postcentral Gyrus
24	-45	-36	-3	Right Middle Frontal Gyrus

24	39	-21	3	Left Inferior Frontal Gyrus
24	-6	30	66	Right Paracentral Lobule
23	51	-15	39	Left Middle Frontal Gyrus
22	51	54	48	Left Inferior Parietal Lobule
22	42	-12	27	Left Middle Frontal Gyrus
22	42	-48	9	Left Middle Frontal Gyrus
21	33	-48	18	Left Middle Frontal Gyrus
21	18	84	-15	Left Lingual Gyrus
20	36	-48	18	Left Middle Frontal Gyrus
17	-45	-39	-15	Right Inferior Frontal Gyrus
17	-9	81	0	Right Lingual Gyrus
17	27	-3	3	Left Lentiform Nucleus
16	24	75	-30	Left Pyramis
16	30	78	27	Left Superior Occipital Gyrus
14	57	48	12	Left Superior Temporal Gyrus
14	-27	27	27	Right Insula
14	-6	45	63	Right Postcentral Gyrus
13	15	-48	36	Left Superior Frontal Gyrus
13	66	36	-21	Left Inferior Temporal Gyrus
13	-21	87	-12	Right Fusiform Gyrus
12	-36	84	0	Right Middle Occipital Gyrus
12	-12	-12	12	Right Caudate
12	-39	87	12	Right Middle Occipital Gyrus
12	66	18	18	Left Postcentral Gyrus
12	-60	0	24	Right Precentral Gyrus
12	-42	39	66	Right Postcentral Gyrus
11	-63	54	30	Right Supramarginal Gyrus
11	-12	-3	-12	Right Subcallosal Gyrus
11	3	21	15	Left Thalamus
11	42	45	48	Left Inferior Parietal Lobule
11	63	51	27	Left Supramarginal Gyrus
10	-48	60	51	Right Inferior Parietal Lobule
10	48	51	-6	Left Middle Temporal Gyrus
10	-69	27	-6	Right Middle Temporal Gyrus
8	36	24	60	Left Precentral Gyrus

8	-39	21	39	Right Postcentral Gyrus
8	-54	39	57	Right Inferior Parietal Lobule
7	-42	-18	-30	Right Superior Temporal Gyrus
7	-42	15	18	Right Insula
6	-9	-36	-6	Right Anterior Cingulate
5	-15	69	36	Right Precuneus
5	-42	-18	-30	Right Superior Temporal Gyrus
5	-42	-33	15	Right Middle Frontal Gyrus
5	-48	-15	18	Right Inferior Frontal Gyrus
4	30	-45	36	Left Middle Frontal Gyrus
4	-18	12	69	Right Superior Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S101: Coordinates of the contrast metacognition task of multiplication vs fixation, font control task, mathematical operation of addition level 1 and metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain area
76	42	-9	36	Left Middle Frontal Gyrus
68	42	-12	27	Left Middle Frontal Gyrus
53	30	-18	33	Left Middle Frontal Gyrus
44	-6	57	15	Right Posterior Cingulate
37	51	54	-6	Left Inferior Temporal Gyrus
32	57	51	-9	Left Middle Temporal Gyrus
27	-27	-6	12	Right Lentiform Nucleus
26	0	81	18	Left Cuneus
20	15	-12	-3	Left Lentiform Nucleus
18	-24	45	66	Right Postcentral Gyrus
18	42	30	51	Left Postcentral Gyrus
18	48	-33	24	Left Middle Frontal Gyrus
17	-54	-18	15	Right Inferior Frontal Gyrus
16	-48	-24	-6	Right Inferior Frontal Gyrus
16	-30	-48	36	Right Superior Frontal Gyrus
15	9	-51	0	Left Medial Frontal Gyrus

15	-12	-18	6	Right Caudate
14	39	75	24	Left Middle Temporal Gyrus
14	9	-18	-24	Left Rectal Gyrus
14	-60	39	54	Right Inferior Parietal Lobule
14	30	9	0	Left Lentiform Nucleus
13	9	-12	-30	Left Rectal Gyrus
13	3	-24	54	Left Superior Frontal Gyrus
13	0	-60	15	Left Medial Frontal Gyrus
12	24	12	51	Left Precentral Gyrus
12	-9	90	-24	Right Uvula
12	-51	24	21	Right Postcentral Gyrus
12	33	72	18	Left Middle Temporal Gyrus
12	27	57	30	Left Precuneus
11	33	33	-3	Left Caudate
11	-63	39	-24	Right Inferior Temporal Gyrus
11	-57	-24	15	Right Inferior Frontal Gyrus
11	42	15	66	Left Precentral Gyrus
11	6	-9	-6	Left Caudate
11	57	15	36	Left Precentral Gyrus
10	48	-3	15	Left Inferior Frontal Gyrus
10	-30	-3	-3	Right Lentiform Nucleus
10	54	36	12	Left Superior Temporal Gyrus
10	3	60	45	Left Precuneus
10	-15	-3	-30	Right Uncus
10	3	-48	-6	Left Medial Frontal Gyrus
10	21	66	-27	Left Pyramis
10	0	66	39	Right Precuneus
10	33	72	18	Left Middle Temporal Gyrus
10	-36	-60	9	Right Middle Frontal Gyrus
10	27	60	33	Left Precuneus
10	-3	-42	-27	Right Orbital Gyrus
9	-57	30	-3	Right Middle Temporal Gyrus
9	48	27	-15	Left Middle Temporal Gyrus
8	-39	78	36	Right Precuneus
7	-24	-39	39	Right Superior Frontal Gyrus

7	57	24	-6	Left Middle Temporal Gyrus
7	9	30	27	Left Cingulate Gyrus
7	57	15	36	Left Precentral Gyrus
6	30	48	48	Left Precuneus
6	-45	-36	-15	Left Middle Frontal Gyrus
6	21	27	15	Left Thalamus
4	-15	-3	-30	Right Uncus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S102: Coordinates of the contrast metacognition task of division vs fixation, font control task, mathematical operation of addition level 1 and metacognition task of control level 1.

Voxels	Peak x	Peak y	Peak z	Brain area
58	42	-21	36	Left Precentral Gyrus
48	9	-12	6	Left Caudate
37	39	-3	24	Left Precentral Gyrus
35	-15	-15	-9	Right Lentiform Nucleus
34	-39	78	36	Right Precuneus
31	54	54	-9	Left Middle Temporal Gyrus
28	-42	-21	-12	Right Inferior Frontal Gyrus
27	-12	57	12	Right Posterior Cingulate
26	27	72	30	Left Cuneus
26	0	66	42	Right Precuneus
26	60	51	-9	Left Inferior Temporal Gyrus
24	-6	48	-33	Right Cerebellar Tonsil
24	6	-9	-6	Left Caudate
22	48	21	42	Left Postcentral Gyrus
21	-51	36	-39	Right Cerebellar Tonsil
20	-51	15	33	Right Postcentral Gyrus
20	-45	12	30	Right Precentral Gyrus
19	-12	-6	15	Right Caudate
18	42	-30	33	Left Middle Frontal Gyrus
18	-6	57	15	Right Posterior Cingulate

17	-51	-3	-33	Right Middle Temporal Gyrus
16	15	57	-15	Left Declive
15	-54	48	-42	Right Cerebellar Tonsil
15	6	48	9	Left Posterior Cingulate
15	-54	66	42	Right Inferior Parietal Lobule
14	-24	63	-21	Right Declive
14	-51	18	42	Right Postcentral Gyrus
14	24	51	66	Left Postcentral Gyrus
14	9	39	-39	Left Cerebellar Tonsil
13	-51	39	-42	Right Cerebellar Tonsil
13	-33	63	15	Right Middle Temporal Gyrus
12	-42	69	12	Right Middle Temporal Gyrus
12	60	12	33	Left Precentral Gyrus
12	54	-24	-6	Left Inferior Frontal Gyrus
12	-36	33	60	Right Postcentral Gyrus
12	-15	54	36	Right Precuneus
12	-54	-33	-15	Right Inferior Frontal Gyrus
12	-12	-51	42	Right Superior Frontal Gyrus
12	-21	48	33	Right Precuneus
12	63	45	18	Left Superior Temporal Gyrus
11	-36	69	12	Right Middle Occipital Gyrus
11	21	96	15	Left Middle Occipital Gyrus
11	15	84	-15	Left Lingual Gyrus
11	-9	-6	9	Right Caudate
10	39	51	-24	Left Culmen
10	30	78	24	Left Superior Occipital Gyrus
10	6	78	54	Left Precuneus
10	-15	63	-48	Right Inferior Semi-Lunar Lobule
10	-60	54	42	Right Inferior Parietal Lobule
10	36	-51	18	Left Middle Frontal Gyrus
9	-48	15	15	Right Insula
9	-15	-15	-9	Right Lentiform Nucleus
8	21	-39	9	Left Medial Frontal Gyrus
8	60	12	30	Left Precentral Gyrus
8	33	-42	6	Left Middle Frontal Gyrus

8	42	57	30	Left Angular Gyrus
8	-24	30	30	Right Cingulate Gyrus
7	-69	27	-9	Right Middle Temporal Gyrus
5	-24	24	-21	Right Parahippocampal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Brain Coordinates of Mathematical Cognition

Figures S6-S12 depict the clusters surviving the contrast across several conditions. In Tables S103-S110, the results of the whole-brain analyses are summarized.

Figure S6. Brain responses comparing operation type across all difficulties.

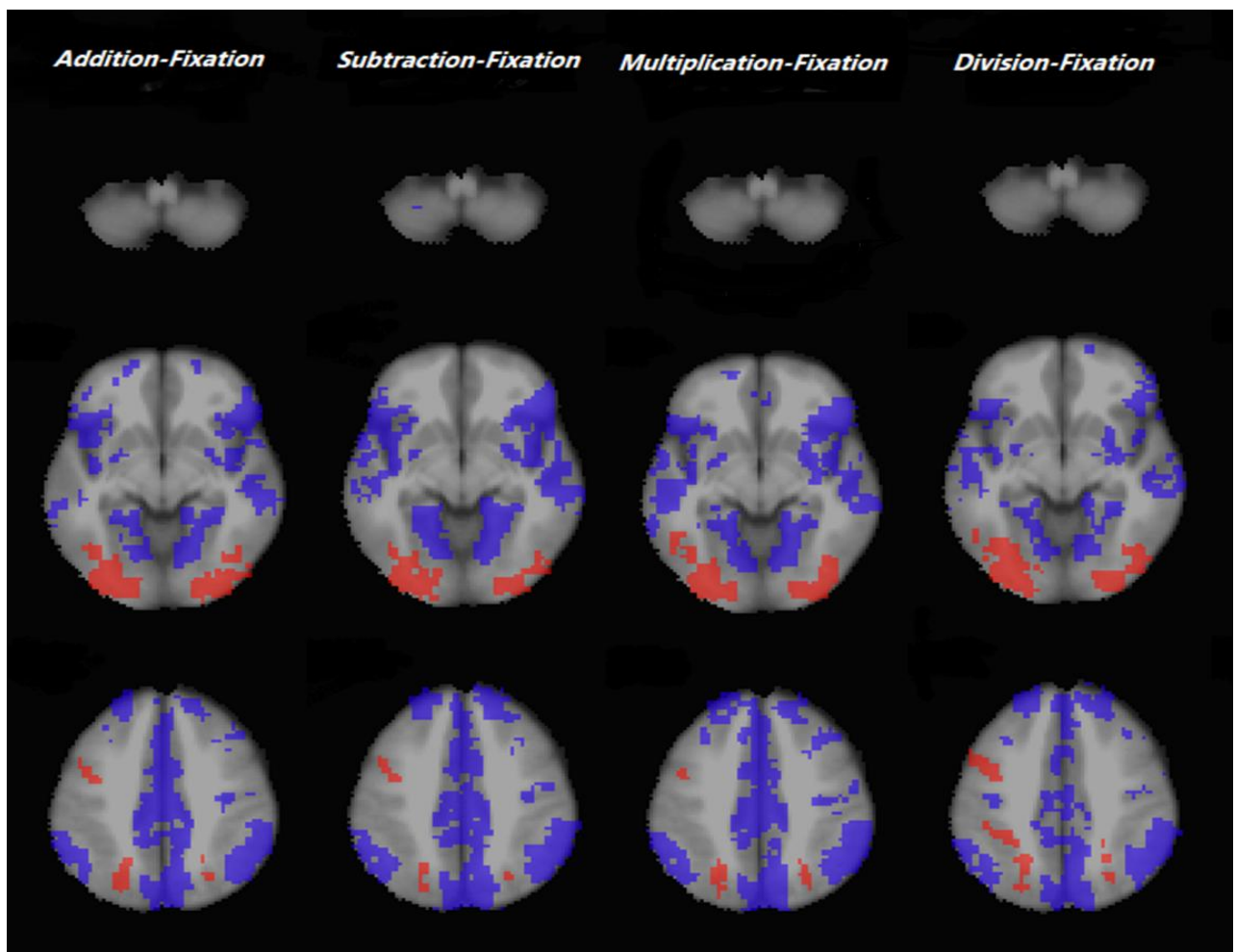


Figure S7: Clusters surviving the contrast division level 2 vs fixation.

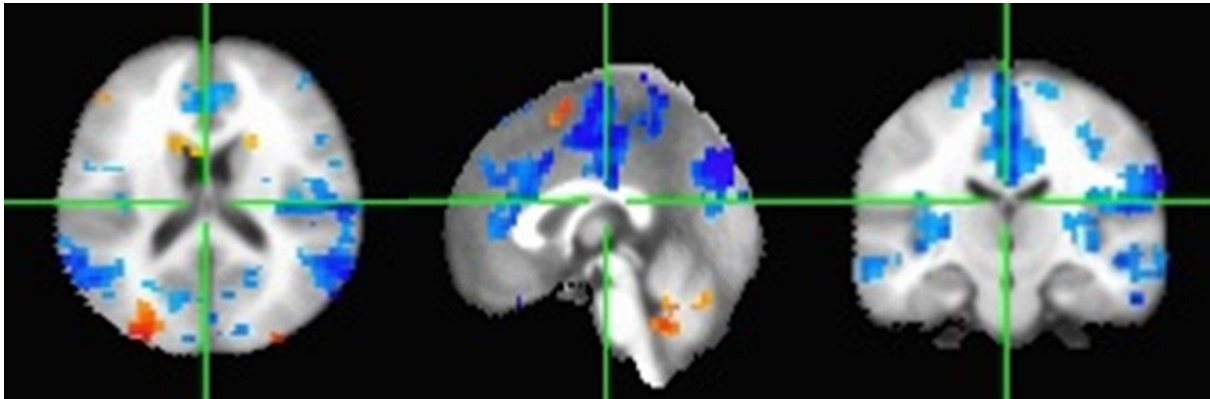


Table S103: Coordinates of the contrast mathematical tasks vs fixation.

Voxels	Peak x	Peak y	Peak z	Brain area
8618	-3	84	48	Right Precuneus
6988	0	84	48	Left Precuneus
2702	-57	-21	-6	Right Inferior Frontal Gyrus
2674	12	-6	-33	Left Uncus
2634	57	-18	-3	Left Inferior Frontal Gyrus
2468	54	60	45	Left Inferior Parietal Lobule
1581	33	96	-9	Left Inferior Occipital Gyrus
1537	30	87	-18	Left Declive
1462	51	-3	51	Left Precentral Gyrus
1263	27	99	-6	Left Lingual Gyrus
1260	-39	90	-9	Right Inferior Occipital Gyrus
1244	21	-60	33	Left Superior Frontal Gyrus
1072	24	99	12	Left Middle Occipital Gyrus
978	15	72	60	Left Superior Parietal Lobule
915	-24	90	-18	Right Fusiform Gyrus
634	-45	90	0	Right Middle Occipital Gyrus
615	51	-6	48	Left Middle Frontal Gyrus
584	-18	63	-9	Right Culmen
431	-21	-15	0	Right Lentiform Nucleus
420	0	-69	18	Left Medial Frontal Gyrus
399	-27	72	60	Right Superior Parietal Lobule

212	-48	-15	51	Right Middle Frontal Gyrus
211	-39	-27	54	Right Superior Frontal Gyrus
205	-18	69	-12	Right Declive
191	-42	-3	-6	Right Insula
188	12	66	-9	Left Culmen
181	-6	-18	6	Right Caudate
178	21	45	72	Left Postcentral Gyrus
171	39	12	3	Left Insula
123	-30	6	51	Right Precentral Gyrus
114	-30	6	51	Right Precentral Gyrus
102	45	63	-48	Left Cerebellar Tonsil
99	-6	78	-42	Right Inferior Semi-Lunar Lobule
95	15	-30	3	Left Anterior Cingulate
79	9	42	0	Left Parahippocampal Gyrus
79	0	24	-6	Posterior Commissure
78	3	48	-36	Left Cerebellar Tonsil
63	15	-9	6	Left Lentiform Nucleus
62	0	12	15	Left Thalamus
61	15	-12	9	Left Caudate
56	-3	78	-27	Right Pyramis
54	54	3	-39	Left Inferior Temporal Gyrus
49	-3	72	-27	Right Pyramis of Vermis
43	30	84	-42	Left Inferior Semi-Lunar Lobule
43	-3	33	0	Right Thalamus
40	48	72	-30	Left Tuber
40	0	-39	-33	Right Orbital Gyrus
39	0	51	-39	Right Cerebellar Tonsil
37	54	36	30	Left Supramarginal Gyrus
33	-57	9	-12	Right Middle Temporal Gyrus
32	0	-39	-30	Left Orbital Gyrus
30	21	90	-33	Left Pyramis
24	30	-12	-24	Left Superior Temporal Gyrus
24	-18	-30	9	Right Anterior Cingulate

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order

being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Figure S8: Clusters surviving the contrast multiplication level 2 vs font control task level 2.

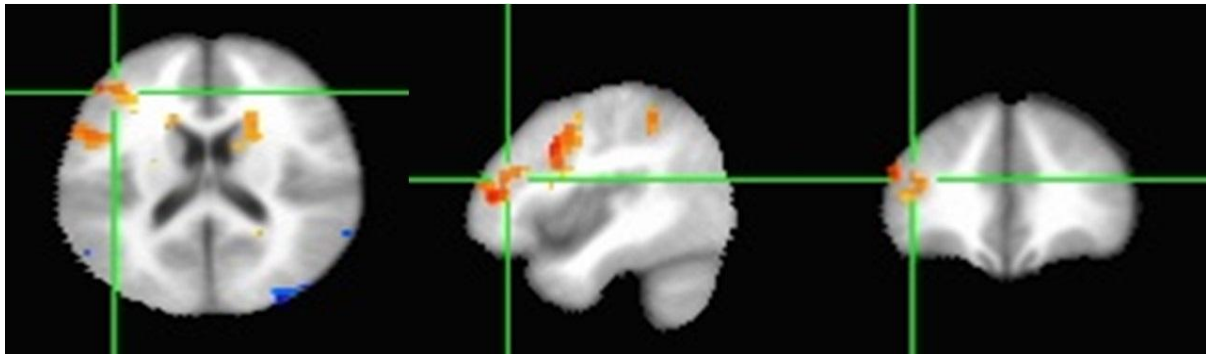


Table S104: Coordinates of the contrast mathematical tasks vs font control task

Voxels	Peak x	Peak y	Peak z	Brain area
443	54	-18	42	Left Middle Frontal Gyrus
365	3	84	45	Left Precuneus
331	51	51	57	Left Inferior Parietal Lobule
284	-39	-57	24	Right Superior Frontal Gyrus
274	57	33	57	Left Postcentral Gyrus
270	51	-3	51	Left Precentral Gyrus
245	-45	3	60	Right Middle Frontal Gyrus
212	-60	66	-3	Right Middle Occipital Gyrus
152	-63	60	0	Right Middle Temporal Gyrus
144	27	-12	69	Left Superior Frontal Gyrus
121	-45	69	-27	Right Tuber
120	0	27	27	Left Cingulate Gyrus
118	-24	72	-12	Right Declive
115	48	-45	12	Left Inferior Frontal Gyrus
113	3	69	6	Left Cuneus
109	33	60	-18	Left Declive
109	57	51	-24	Left Tuber
109	-12	-3	21	Right Caudate
107	-42	9	66	Right Precentral Gyrus
93	33	57	51	Left Superior Parietal Lobule
81	-36	36	-24	Right Culmen

80	0	3	54	Left Medial Frontal Gyrus
77	-60	63	33	Right Supramarginal Gyrus
70	-27	72	-24	Right Uvula
67	-3	90	36	Right Cuneus
64	33	48	-21	Left Culmen
60	-48	36	66	Right Postcentral Gyrus
58	57	63	27	Left Superior Temporal Gyrus
57	-6	84	42	Right Precuneus
56	-48	33	-24	Right Fusiform Gyrus
52	57	66	-9	Left Middle Occipital Gyrus
51	-51	-36	-15	Right Inferior Frontal Gyrus
50	6	-12	18	Left Caudate
45	-30	48	15	Right Superior Temporal Gyrus
43	51	57	-9	Left Middle Temporal Gyrus
42	-21	-12	-6	Right Lentiform Nucleus
37	21	0	9	Left Lentiform Nucleus
36	45	63	30	Left Angular Gyrus
36	21	24	-6	Left Parahippocampal Gyrus
36	-57	36	60	Right Inferior Parietal Lobule
33	-3	3	51	Right Medial Frontal Gyrus
33	-12	72	57	Right Superior Parietal Lobule
31	-51	48	-39	Right Cerebellar Tonsil
30	-42	15	-30	Right Inferior Temporal Gyrus
28	54	66	-12	Left Fusiform Gyrus
24	-6	-30	-21	Right Rectal Gyrus
23	-9	51	-24	Right Fastigium
19	0	-24	24	Left Anterior Cingulate
19	60	60	-12	Left Inferior Temporal Gyrus
18	15	99	-9	Left Lingual Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Figure S9: Clusters surviving the contrast addition level 3 vs multiplication level 3.

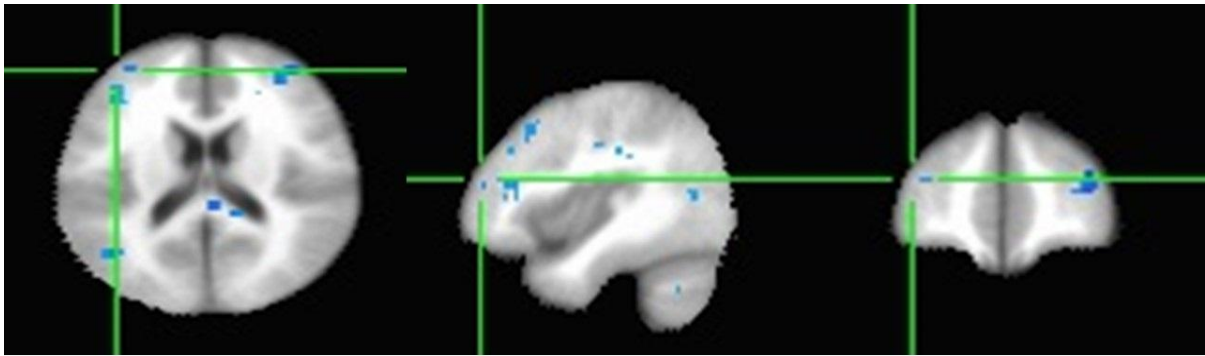


Table S105: Coordinates of the contrast between different operations of mathematical tasks.

Voxels	Peak x	Peak y	Peak z	Brain area
144	-18	-24	66	Right Superior Frontal Gyrus
89	30	0	15	Left Insula
71	3	57	72	Left Postcentral Gyrus
66	-3	69	60	Right Superior Parietal Lobule
64	0	42	33	Left Cingulate Gyrus
55	-48	39	66	Right Postcentral Gyrus
54	0	75	39	Right Precuneus
53	21	60	3	Left Lingual Gyrus
51	66	51	-3	Left Middle Temporal Gyrus
47	39	75	45	Left Precuneus
45	60	3	9	Left Superior Temporal Gyrus
41	24	-6	72	Left Superior Frontal Gyrus
41	-39	-51	12	Right Middle Frontal Gyrus
38	45	-45	12	Left Middle Frontal Gyrus
37	36	78	48	Left Superior Parietal Lobule
36	-45	69	-45	Right Inferior Semi-Lunar Lobule
36	-24	-3	-9	Right Subcallosal Gyrus
33	9	-24	3	Left Caudate
33	-6	30	6	Right Thalamus
32	-42	39	42	Right Inferior Parietal Lobule
30	66	36	27	Left Inferior Parietal Lobule
30	0	39	21	Left Posterior Cingulate
29	54	-15	27	Left Inferior Frontal Gyrus

28	-24	69	9	Right Cuneus
27	6	81	6	Left Cuneus
25	-42	84	15	Right Middle Occipital Gyrus
24	-57	66	33	Right Angular Gyrus
22	-45	42	-48	Right Cerebellar Tonsil
22	-18	-9	24	Right Cingulate Gyrus
20	-12	-48	0	Right Medial Frontal Gyrus
18	9	87	-27	Left Pyramis
17	30	57	-36	Left Cerebellar Tonsil
17	0	9	15	Left Thalamus
17	-39	24	36	Right Precentral Gyrus
17	-39	-6	-24	Right Superior Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Figure S10: Clusters surviving the contrast addition level 1 vs fixation.

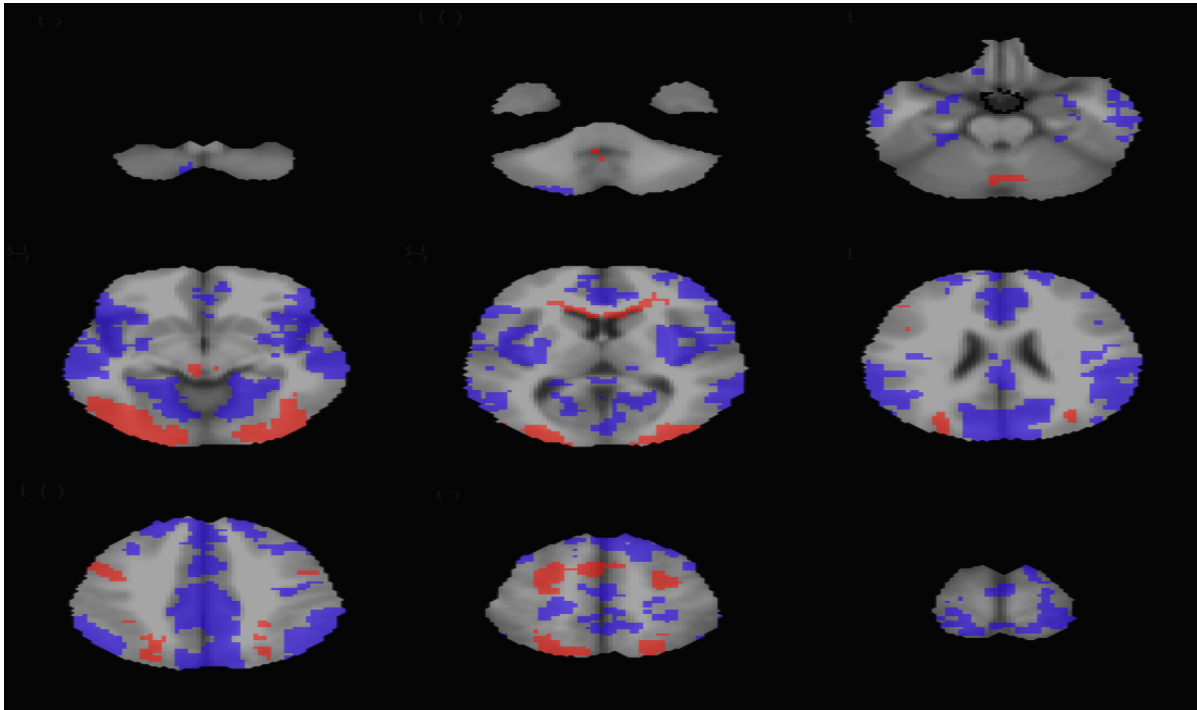


Table S106: Coordinates of the contrast mathematical tasks of addition vs fixation and control task. (ADD1-FIX, ADD2-FIX, ADD3-FIX, ADD1,2,3 -FIX, ADD1-CONT1, ADD2-CONT2, ADD3-CONT3, ADD1,2,3 -CONT1,2,3)

Voxels	Peak x	Peak y	Peak z	Brain area
10813	-6	84	45	Right Precuneus
8436	-3	84	48	Right Precuneus
4706	-3	81	48	Right Precuneus
3673	0	87	42	Left Cuneus
3007	57	-18	-3	Left Inferior Frontal Gyrus
2468	54	60	45	Left Inferior Parietal Lobule
2414	-54	-27	-9	Right Inferior Frontal Gyrus
1600	45	66	51	Left Inferior Parietal Lobule
1355	33	93	-15	Left Inferior Occipital Gyrus
1263	27	99	-6	Left Lingual Gyrus
1237	39	81	-15	Left Declive
854	-39	90	-9	Right Inferior Occipital Gyrus
760	30	87	-21	Left Declive
660	-18	93	-18	Right Fusiform Gyrus
608	-36	96	-6	Right Inferior Occipital Gyrus
601	51	-3	51	Left Precentral Gyrus
399	-36	93	9	Right Middle Occipital Gyrus
317	-27	72	60	Right Superior Parietal Lobule
310	-24	72	57	Right Superior Parietal Lobule
288	51	-6	48	Left Middle Frontal Gyrus
281	3	-6	60	Left Superior Frontal Gyrus
260	-21	-15	0	Right Lentiform Nucleus
221	21	-57	39	Left Superior Frontal Gyrus
211	-39	-27	54	Right Superior Frontal Gyrus
187	30	-3	69	Left Superior Frontal Gyrus
181	-6	-18	6	Right Caudate
180	54	-9	45	Left Middle Frontal Gyrus
158	54	36	57	Left Inferior Parietal Lobule
153	24	78	54	Left Precuneus
152	-63	60	0	Right Middle Temporal Gyrus
141	24	-57	36	Left Superior Frontal Gyrus

137	45	-15	48	Left Middle Frontal Gyrus
130	36	-24	57	Left Middle Frontal Gyrus
126	-21	66	54	Right Superior Parietal Lobule
123	42	-12	33	Left Middle Frontal Gyrus
118	-24	72	-12	Right Declive
117	24	-60	33	Left Superior Frontal Gyrus
114	-30	6	51	Right Precentral Gyrus
109	3	-3	69	Left Superior Frontal Gyrus
105	51	-9	48	Left Middle Frontal Gyrus
103	54	36	60	Left Inferior Parietal Lobule
102	45	63	-48	Left Cerebellar Tonsil
87	-6	78	-39	Right Inferior Semi-Lunar Lobule
78	-33	3	51	Right Middle Frontal Gyrus
77	-60	63	33	Right Supramarginal Gyrus
74	-54	75	-6	Right Middle Occipital Gyrus
71	30	66	-18	Left Declive
70	21	-9	72	Left Superior Frontal Gyrus
68	30	69	60	Left Superior Parietal Lobule
67	-6	-21	3	Right Caudate
64	33	48	-21	Left Culmen
62	-24	-12	72	Right Superior Frontal Gyrus
56	-48	33	-24	Right Fusiform Gyrus
56	-3	78	-27	Right Pyramis
51	-51	-36	-15	Right Inferior Frontal Gyrus
46	54	-15	36	Left Middle Frontal Gyrus
45	3	30	-3	Left Thalamus
45	15	-63	-9	Left Superior Frontal Gyrus
43	15	0	21	Left Caudate
42	-39	15	42	Right Precentral Gyrus
40	48	72	-30	Left Tuber
38	0	33	0	Right Inferior Parietal Lobule
36	-42	15	42	Right Precentral Gyrus
36	45	63	30	Left Angular Gyrus
33	0	6	57	Left Medial Frontal Gyrus
32	-42	-9	33	Right Inferior Frontal Gyrus

31	-6	-30	-33	Right Orbital Gyrus
31	21	36	-54	Right Precuneus
30	-9	72	-21	Right Declive
30	21	90	-33	Left Pyramis
29	0	45	-36	Left Cerebellar Tonsil
28	3	48	-33	Left Cerebellar Tonsil
28	54	66	-12	Left Fusiform Gyrus
27	-24	-6	-24	Right Uncus
27	6	63	-60	Right Inferior Temporal Gyrus
25	-21	-15	3	Right Lentiform Nucleus
24	15	78	-12	Left Declive
24	30	-12	-24	Left Superior Temporal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S107: Coordinates of the contrast mathematical task of subtraction vs fixation and control task. (SUB1-FIX, SUB2-FIX, SUB3-FIX, SUB1,2,3-FIX, SUB1-CONT1, SUB2-CONT2, SUB3-CONT3, SUB1,2,3-CONT1,2,3)

Voxels	Peak x	Peak y	Peak z	Brain area
10613	-6	81	51	Right Precuneus
5125	-3	84	48	Right Precuneus
2441	57	-18	-3	Left Inferior Frontal Gyrus
2280	54	-21	-6	Left Inferior Frontal Gyrus
2100	-60	-21	0	Right Inferior Frontal Gyrus
1836	-51	57	57	Right Inferior Parietal Lobule
1592	54	63	42	Left Inferior Parietal Lobule
1537	30	87	-18	Left Declive
1531	0	84	48	Left Precuneus
1514	0	87	42	Left Cuneus
1436	33	93	-12	Left Inferior Occipital Gyrus
1409	54	-24	-6	Left Inferior Frontal Gyrus
1244	21	-60	33	Left Superior Frontal Gyrus
1176	39	78	-18	Left Declive

953	-42	90	-12	Right Inferior Occipital Gyrus
842	-39	90	-9	Right Inferior Occipital Gyrus
634	-45	90	0	Right Middle Occipital Gyrus
615	51	-6	48	Left Middle Frontal Gyrus
610	54	-9	45	Left Middle Frontal Gyrus
600	24	93	3	Left Middle Occipital Gyrus
443	42	-12	36	Left Middle Frontal Gyrus
420	0	-69	18	Left Medial Frontal Gyrus
345	-27	72	60	Right Superior Parietal Lobule
324	-60	-24	-3	Right Inferior Frontal Gyrus
275	-36	90	-9	Right Inferior Occipital Gyrus
274	57	33	57	Left Postcentral Gyrus
220	-12	39	-6	Right Culmen
188	3	84	45	Left Precuneus
179	-54	75	-9	Right Middle Occipital Gyrus
162	-27	3	54	Right Middle Frontal Gyrus
147	-6	-18	6	Right Caudate
140	-33	-36	54	Right Superior Frontal Gyrus
135	-6	-21	6	Right Caudate
128	-36	-27	57	Right Superior Frontal Gyrus
123	-30	6	51	Right Precentral Gyrus
112	54	-15	39	Left Middle Frontal Gyrus
106	27	-12	69	Left Superior Frontal Gyrus
105	15	69	-9	Left Declive
101	27	-9	69	Left Superior Frontal Gyrus
98	-30	3	51	Right Middle Frontal Gyrus
96	-24	-6	72	Right Superior Frontal Gyrus
95	15	-30	3	Left Anterior Cingulate
81	-36	36	-24	Right Culmen
79	9	42	0	Left Parahippocampal Gyrus
76	24	-15	69	Left Superior Frontal Gyrus
74	36	-30	51	Left Superior Frontal Gyrus
71	42	-9	36	Left Middle Frontal Gyrus
62	15	-66	30	Left Superior Frontal Gyrus
62	18	51	72	Left Postcentral Gyrus

61	15	-12	9	Left Caudate
61	39	-9	36	Left Middle Frontal Gyrus
59	-42	-9	33	Right Inferior Frontal Gyrus
57	-6	84	42	Right Precuneus
48	0	27	-3	Posterior Commissure
46	0	45	-36	Left Cerebellar Tonsil
44	-45	-9	36	Right Middle Frontal Gyrus
44	-27	-9	72	Right Superior Frontal Gyrus
43	51	57	-9	Left Middle Temporal Gyrus
41	6	-24	3	Left Caudate
40	36	-21	54	Left Superior Frontal Gyrus
38	27	51	-15	Left Culmen
37	-24	69	57	Right Superior Parietal Lobule
37	-3	-21	9	Right Caudate
36	-30	69	30	Right Precuneus
36	3	75	-3	Left Lingual Gyrus
35	-57	6	-36	Right Inferior Temporal Gyrus
35	27	54	-12	Left Declive
35	42	-27	27	Left Middle Frontal Gyrus
33	-12	72	57	Right Superior Parietal Lobule
32	-6	78	-42	Right Inferior Semi-Lunar Lobule
32	3	-6	60	Left Superior Frontal Gyrus
32	15	-9	9	Left Caudate
31	-66	-9	9	Right Precentral Gyrus
31	-3	78	18	Right Cuneus
30	-42	15	-30	Right Inferior Temporal Gyrus
29	-18	60	-21	Right Culmen
29	21	27	-3	Left Thalamus
28	-12	-39	60	Right Superior Frontal Gyrus
25	36	-57	24	Left Superior Frontal Gyrus
25	39	-42	9	Left Middle Frontal Gyrus
25	57	-24	12	Left Inferior Frontal Gyrus
24	-39	54	-30	Right Culmen
24	-6	-30	-21	Right Rectal Gyrus
22	-21	-15	12	Right Caudate

22	48	-30	36	Left Middle Frontal Gyrus
19	60	60	-12	Left Inferior Temporal Gyrus
18	15	99	-9	Left Lingual Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Figure S11: Clusters surviving the contrast multiplication level 3 vs font control level 3.

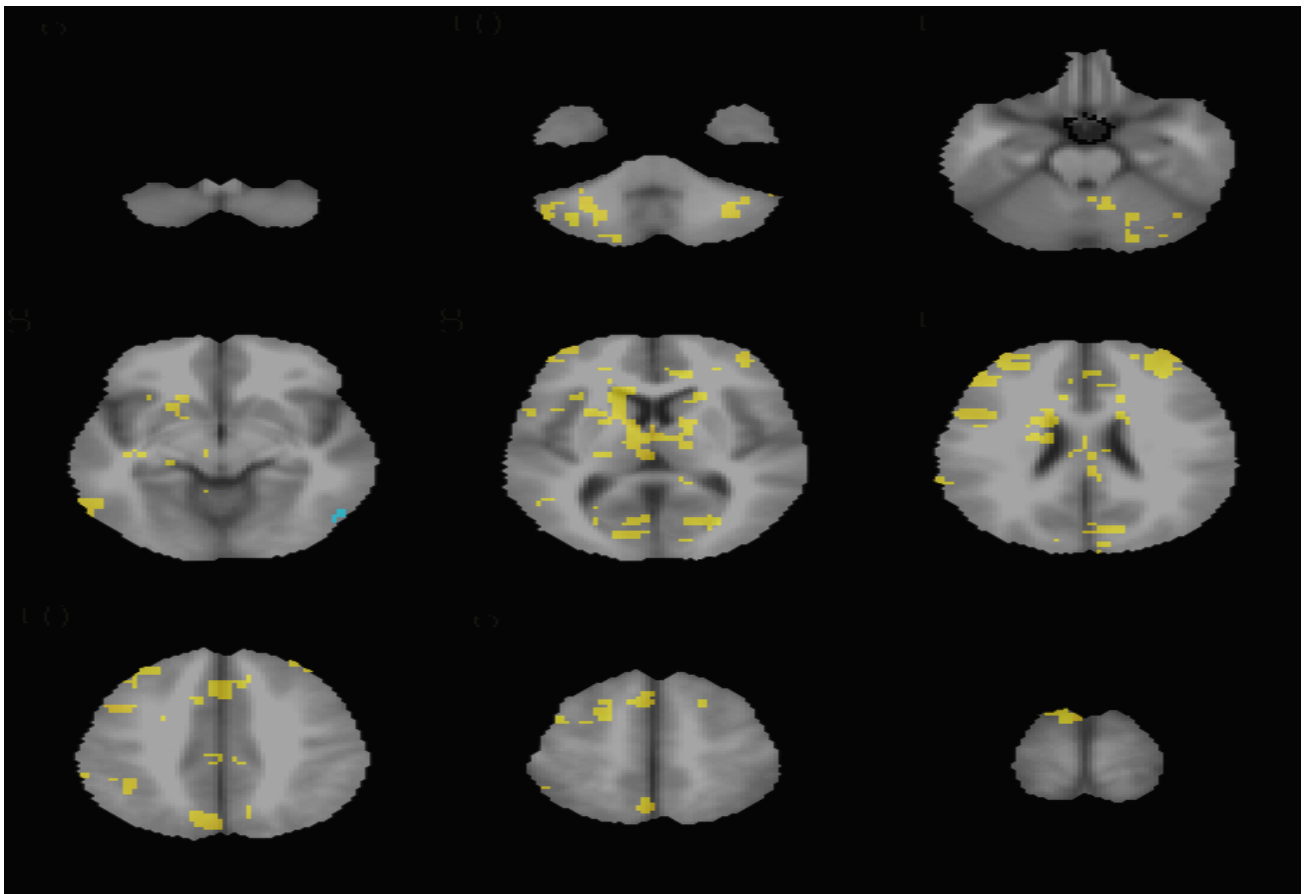


Table S108: Coordinates of the contrast mathematical task of multiplication Vs fixation and control task (MUL1-FIX, MUL2-FIX, MUL3-FIX, MUL1,2,3-FIX, MUL1-CONT1, MUL2-CONT2, MUL3-CONT3, MUL1,2,3-CONT1,2,3).

Voxels	Peak x	Peak y	Peak z	Brain area
12454	0	87	42	Left Cuneus
9908	0	84	45	Right Precuneus
5107	-6	81	51	Right Precuneus
2351	54	-21	-6	Left Inferior Frontal Gyrus

1581	33	96	-9	Left Inferior Occipital Gyrus
1462	51	-3	51	Left Precentral Gyrus
1189	30	78	-21	Left Declive
915	-24	90	-18	Right Fusiform Gyrus
849	24	93	3	Left Middle Occipital Gyrus
758	36	93	-9	Left Inferior Occipital Gyrus
690	-51	57	57	Right Inferior Parietal Lobule
559	-39	90	-9	Right Inferior Occipital Gyrus
541	-36	93	-9	Right Inferior Occipital Gyrus
470	57	57	39	Left Inferior Parietal Lobule
463	-6	84	45	Right Precuneus
431	-21	-15	0	Right Lentiform Nucleus
399	-27	72	60	Right Superior Parietal Lobule
378	-36	93	9	Right Middle Occipital Gyrus
356	24	-57	36	Left Superior Frontal Gyrus
324	0	15	66	Left Medial Frontal Gyrus
298	36	-63	15	Left Middle Frontal Gyrus
284	-39	-57	24	Right Superior Frontal Gyrus
272	-24	69	57	Right Superior Parietal Lobule
212	-60	66	-3	Right Middle Occipital Gyrus
205	-18	69	-12	Right Declive
191	-42	-3	-6	Right Insula
171	39	12	3	Left Insula
165	-57	69	3	Right Middle Occipital Gyrus
160	51	-6	48	Left Middle Frontal Gyrus
157	9	45	0	Left Culmen
156	30	0	69	Left Superior Frontal Gyrus
151	36	-27	54	Left Superior Frontal Gyrus
142	-24	69	54	Right Superior Parietal Lobule
127	-27	6	51	Right Middle Frontal Gyrus
124	27	-12	69	Left Superior Frontal Gyrus
121	-45	69	-27	Right Tuber
120	0	27	27	Left Cingulate Gyrus
115	48	-45	12	Left Inferior Frontal Gyrus
113	3	69	6	Left Cuneus

110	57	36	57	Left Postcentral Gyrus
109	-12	-3	21	Right Caudate
107	-42	9	66	Right Precentral Gyrus
99	-6	78	-42	Right Inferior Semi-Lunar Lobule
98	0	75	48	Left Precuneus
93	33	57	51	Left Superior Parietal Lobule
84	-27	-12	69	Right Superior Frontal Gyrus
82	3	-6	60	Left Superior Frontal Gyrus
79	0	24	-6	Posterior Commissure
78	3	48	-36	Left Cerebellar Tonsil
72	0	63	57	Left Precuneus
70	-27	72	-24	Right Uvula
69	-30	6	51	Right Precentral Gyrus
68	42	54	63	Left Superior Parietal Lobule
67	-3	90	36	Right Cuneus
67	30	63	-18	Left Declive
62	0	12	15	Left Thalamus
60	-48	36	66	Right Postcentral Gyrus
58	57	63	27	Left Superior Temporal Gyrus
56	-54	-21	42	Right Middle Frontal Gyrus
56	42	-12	33	Left Middle Frontal Gyrus
54	-21	96	27	Right Cuneus
54	9	-24	6	Left Caudate
54	54	3	-39	Left Inferior Temporal Gyrus
52	57	66	-9	Left Middle Occipital Gyrus
51	0	-24	24	Left Anterior Cingulate
51	9	42	-3	Left Culmen
49	51	57	-45	Left Cerebellar Tonsil
47	-57	-24	-6	Right Inferior Frontal Gyrus
47	-42	-9	33	Right Inferior Frontal Gyrus
45	-30	48	15	Right Superior Temporal Gyrus
43	-6	-21	6	Right Caudate
37	-66	15	36	Right Postcentral Gyrus
37	-33	57	-27	Right Tuber
37	21	0	9	Left Lentiform Nucleus

37	54	36	30	Left Supramarginal Gyrus
36	21	24	-6	Left Parahippocampal Gyrus
35	33	48	-24	Left Culmen
34	-51	-42	15	Right Middle Frontal Gyrus
34	0	36	0	Right Culmen
34	63	42	24	Left Inferior Parietal Lobule
33	-57	9	-12	Right Middle Temporal Gyrus
33	3	-3	69	Left Superior Frontal Gyrus
33	24	27	-3	Left Thalamus
31	-51	48	-39	Right Cerebellar Tonsil
30	39	15	39	Left Precentral Gyrus
29	-51	69	-6	Right Middle Occipital Gyrus
29	-39	-6	33	Right Inferior Frontal Gyrus
29	3	33	-3	Left Culmen
28	-21	69	9	Right Cuneus
28	42	-48	27	Left Middle Frontal Gyrus
26	15	-60	-9	Left Superior Frontal Gyrus
25	21	-3	51	Left Medial Frontal Gyrus
23	-9	51	-24	Right Fastigium
23	39	51	-27	Left Culmen
20	9	36	-15	Left Culmen

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Table S109: Coordinates of the contrast mathematical task of division Vs fixation and control task (DIV1-FIX, DIV2-FIX, DIV3-FIX, DIV 1,2,3, DIV1-CONT1, DIV2-CONT2, DIV3-CONT3, DIV 1,2,3 -CONT1,2,3).

Voxels	Peak x	Peak y	Peak z	Brain area
10088	-6	81	51	Right Precuneus
6988	0	84	48	Left Precuneus
2702	-57	-21	-6	Right Inferior Frontal Gyrus
2634	57	-18	-3	Left Inferior Frontal Gyrus
2210	-60	-21	-3	Right Inferior Frontal Gyrus

1670	54	-27	-9	Left Inferior Frontal Gyrus
1666	54	-21	-6	Left Inferior Frontal Gyrus
1240	33	96	-9	Left Inferior Occipital Gyrus
1072	24	99	12	Left Middle Occipital Gyrus
978	15	72	60	Left Superior Parietal Lobule
606	-39	90	-9	Right Inferior Occipital Gyrus
584	-18	63	-9	Right Culmen
568	0	87	39	Left Cuneus
557	-36	93	-9	Right Inferior Occipital Gyrus
443	54	-18	42	Left Middle Frontal Gyrus
399	-21	93	-18	Right Fusiform Gyrus
381	54	-9	45	Left Middle Frontal Gyrus
365	3	84	45	Left Precuneus
331	51	51	57	Left Inferior Parietal Lobule
290	51	39	63	Left Inferior Parietal Lobule
263	27	-12	69	Left Superior Frontal Gyrus
245	-45	3	60	Right Middle Frontal Gyrus
242	45	-9	36	Left Middle Frontal Gyrus
239	-24	69	54	Right Superior Parietal Lobule
226	-24	69	57	Right Superior Parietal Lobule
204	-27	72	60	Right Superior Parietal Lobule
195	30	-6	69	Left Superior Frontal Gyrus
188	12	66	-9	Left Culmen
178	21	45	72	Left Postcentral Gyrus
168	-54	75	0	Right Middle Occipital Gyrus
156	-39	-27	54	Right Superior Frontal Gyrus
132	-18	-63	33	Right Superior Frontal Gyrus
127	30	0	69	Left Superior Frontal Gyrus
117	18	-60	33	Left Superior Frontal Gyrus
114	42	-33	42	Left Middle Frontal Gyrus
109	33	60	-18	Left Declive
109	57	51	-24	Left Tuber
107	3	-3	60	Left Medial Frontal Gyrus
98	-57	69	-3	Right Middle Occipital Gyrus
90	-51	-12	54	Right Middle Frontal Gyrus

89	-6	-21	6	Right Caudate
88	-30	6	51	Right Precentral Gyrus
80	0	3	54	Left Medial Frontal Gyrus
70	-21	-12	-3	Right Lentiform Nucleus
68	3	-6	60	Left Superior Frontal Gyrus
67	24	45	72	Left Postcentral Gyrus
63	15	-9	6	Left Lentiform Nucleus
62	-30	-12	69	Right Middle Frontal Gyrus
62	3	-33	60	Left Superior Frontal Gyrus
61	27	-15	66	Left Middle Frontal Gyrus
54	-39	15	42	Right Precentral Gyrus
54	-27	6	51	Right Middle Frontal Gyrus
50	6	-12	18	Left Caudate
50	6	-24	48	Left Superior Frontal Gyrus
49	-3	72	-27	Right Pyramis of Vermis
46	-24	-18	69	Right Superior Frontal Gyrus
46	0	-24	45	Left Medial Frontal Gyrus
44	-45	-3	36	Right Precentral Gyrus
43	-3	33	0	Right Thalamus
43	30	84	-42	Left Inferior Semi-Lunar Lobule
42	-21	-12	-6	Right Lentiform Nucleus
41	-30	3	48	Right Middle Frontal Gyrus
41	36	9	66	Left Precentral Gyrus
39	0	51	-39	Right Cerebellar Tonsil
39	15	-30	3	Left Anterior Cingulate
38	54	-36	-3	Left Inferior Frontal Gyrus
36	9	-24	6	Left Caudate
35	-42	-9	33	Right Inferior Frontal Gyrus
35	-18	-15	3	Right Lentiform Nucleus
34	30	60	-18	Left Declive
34	42	-57	12	Left Middle Frontal Gyrus
33	-39	-48	39	Right Middle Frontal Gyrus
33	-3	3	51	Right Medial Frontal Gyrus
32	0	-39	-30	Left Orbital Gyrus
31	-51	45	-48	Right Cerebellar Tonsil

			202	
31	3	45	-36	Left Cerebellar Tonsil
31	33	-27	48	Left Superior Frontal Gyrus
29	-42	15	60	Right Precentral Gyrus
29	12	-18	-30	Left Orbital Gyrus
29	21	9	72	Left Superior Frontal Gyrus
29	39	18	-36	Left Inferior Temporal Gyrus
28	18	-12	-6	Left Lentiform Nucleus
27	-63	45	48	Right Inferior Parietal Lobule
26	-3	-42	21	Right Medial Frontal Gyrus
25	-54	72	-3	Right Middle Occipital Gyrus
25	-39	63	-15	Right Declive
25	21	-3	-21	Left Uncus
24	-18	-30	9	Right Anterior Cingulate
24	-9	81	-21	Right Declive
24	-3	-54	3	Right Medial Frontal Gyrus
22	60	21	39	Left Postcentral Gyrus
21	-48	60	57	Right Superior Parietal Lobule
21	-27	-54	39	Right Superior Frontal Gyrus
20	-27	93	27	Right Cuneus
20	48	-48	0	Left Inferior Frontal Gyrus
19	0	-24	24	Left Anterior Cingulate
19	18	75	-12	Left Declive
18	0	-57	12	Left Medial Frontal Gyrus

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.

Figure S12: Clusters surviving the contrast division level 2 vs division level 1.

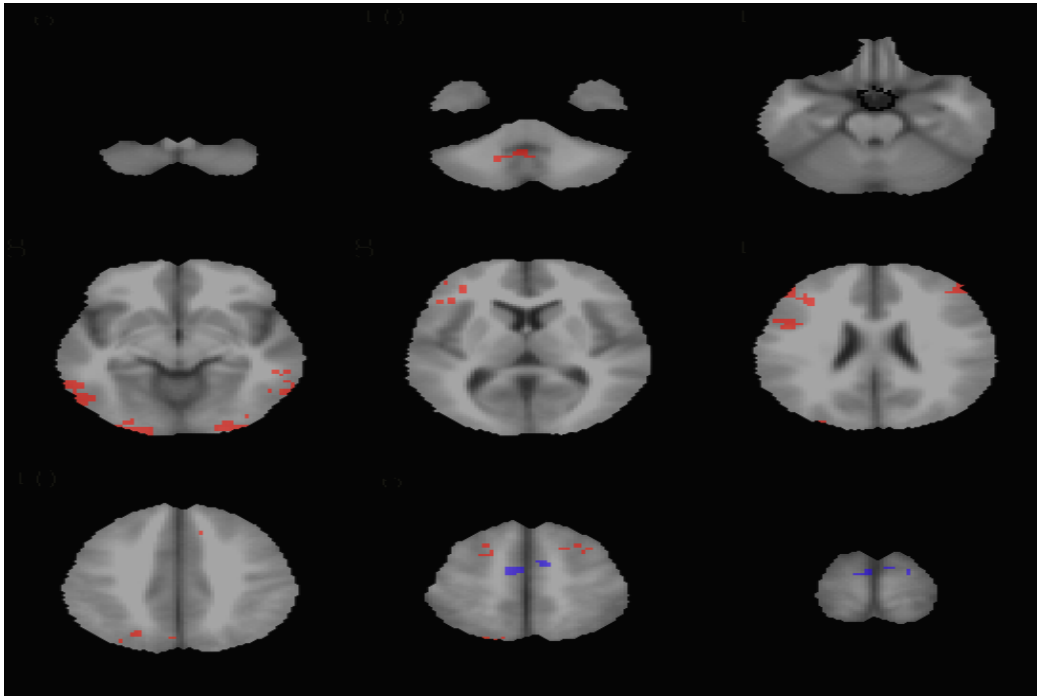


Table S110: Coordinates of the contrast between the same operation of mathematical and control tasks (ADD2-ADD1, ADD3-ADD1, SUB2-SUB1, SUB3-SUB1, MUL2-MUL1, MUL3-MUL1, DIV2-DIV1, DIV3-DIV1, CONT2-CONT1, CONT3-CONT1).

Voxels	Peak x	Peak y	Peak z	Brain area
1128	-27	-12	69	Right Superior Frontal Gyrus
507	-24	90	-15	Right Fusiform Gyrus
467	33	93	-15	Left Inferior Occipital Gyrus
360	36	-63	15	Left Middle Frontal Gyrus
356	30	93	-18	Left Fusiform Gyrus
306	54	42	60	Left Inferior Parietal Lobule
218	-33	96	-6	Right Inferior Occipital Gyrus
203	-24	90	-21	Right Uvula
195	-18	102	-12	Right Lingual Gyrus
183	-6	78	51	Right Precuneus
173	0	6	12	Left Thalamus
160	51	0	51	Left Precentral Gyrus
157	24	102	-6	Left Lingual Gyrus
148	0	6	57	Left Medial Frontal Gyrus
141	51	66	-24	Left Tuber
126	-54	63	-24	Right Tuber

125	-21	66	-42	Right Inferior Semi-Lunar Lobule
103	-24	102	0	Right Cuneus
102	-48	-21	-6	Right Inferior Frontal Gyrus
96	51	57	-9	Left Middle Temporal Gyrus
89	-51	9	30	Right Precentral Gyrus
78	51	63	-9	Left Middle Occipital Gyrus
78	-45	-36	45	Right Middle Frontal Gyrus
65	24	-18	66	Left Superior Frontal Gyrus
59	0	39	21	Left Posterior Cingulate
59	-30	48	42	Right Inferior Parietal Lobule
56	-24	63	-21	Right Declive
54	27	66	57	Left Superior Parietal Lobule
49	15	57	-6	Left Culmen
38	0	75	-24	Left Tuber of Vermis
37	-6	6	60	Right Medial Frontal Gyrus
36	-24	72	60	Right Superior Parietal Lobule
35	21	27	-9	Left Parahippocampal Gyrus
32	-3	54	-42	Right Cerebellar Tonsil
32	-15	30	-9	Right Culmen
30	-24	51	12	Right Posterior Cingulate
28	30	75	-21	Left Declive
26	57	-18	0	Left Inferior Frontal Gyrus
25	30	-21	3	Left Insula
25	9	87	45	Left Precuneus
24	15	0	24	Left Cingulate Gyrus
24	-24	18	-27	Right Parahippocampal Gyrus
23	-21	-15	12	Right Caudate
22	0	81	-21	Right Declive of Vermis

Note: Clusters survive a threshold of $p < 0.01$ FDR corrected for multiple comparisons and a cluster forming threshold of $p < 0.001$. Coordinates are given in Talairach space with the coordinate order being in radiological convention (RAI). Peak corresponds to the coordinates in the brain where a certain cluster was found to have the most intense activation.