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Neurocognitive Foundations of Abstract Reasoning in Middle Childhood

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Abstract: Limited research has jointly examined how error monitoring, multidimensional inhibition, white matter pathways, and daily biological rhythms relate to abstract reasoning during middle childhood, the period in which children aged 7 to 12 years move from concrete to abstract thinking. This systematic review followed PRISMA 2020, searched Scopus, Web of Science, and PubMed between January and March 2026 for neuroscience and cognitive studies published from 2020 to 2026, identified 485 records, and appraised 23 included studies with the Joanna Briggs Institute checklists. Narrative synthesis produced six coded themes showing that children in a task-switching study made more consecutive errors and showed smaller post-error slowing than adults while recruiting the dorsal anterior cingulate cortex and anterior insula, that white matter microstructure was related to age and arithmetic performance, that response inhibition was related to visuospatial working memory in young adults, that far transfer from executive function training was limited, that cognitively engaging physical activity and guided play showed small to moderate benefits, and that sleep and class timing were related to cognitive performance. These findings indicate that abstract reasoning in middle childhood is supported by interacting neural and biological conditions, and the proposed neuropedagogical framework should be treated as a set of hypotheses that require classroom-based experimental testing.

Keywords: Educational Neuroscience; Executive Function; Abstract Reasoning; Error Monitoring; Cognitive Chronobiology.

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INTRODUCTION

Educational neuroscience links evidence on brain function with classroom practice, and it offers teachers an empirical basis for aligning learning experiences with children's cognitive development. Between the ages of 7 and 12 years, children move from reasoning that depends on concrete objects toward reasoning that requires manipulation of mental representations, a transition that draws on executive functions. According to Miyake et al. (2000), executive functions comprise partly separable components of updating, shifting, and inhibition, and Diamond (2013) described working memory, inhibitory control, and cognitive flexibility as core processes that support reasoning and problem solving. A meta-analysis by Spiegel et al. (2021), covering 299 studies and 65,605 elementary school children, reported that relations between executive function components and academic outcomes remained significant throughout the elementary years.

Error monitoring is one mechanism through which executive functions may support reasoning, because it allows the brain to detect a mistake and adjust behavior on later attempts. In the predictive processing account presented by Clark (2013), the brain generates top-down expectations and updates them when prediction errors arise. Work by Botvinick et al. (2004) described how the anterior cingulate cortex monitors conflict so that cognitive control can be adjusted. A review by Ullsperger et al. (2014) outlined the neurophysiological basis of performance monitoring and adaptive behavior, which provides the theoretical background for studying post-error adjustments in children.

Recent developmental studies have described how the error-monitoring system changes during childhood. Research by Dubravac et al. (2022) found that children aged 8, 10, and 12 years and adults showed post-error slowing in Stroop, Simon, and flanker tasks, and that slowing on the first post-error trial declined with age. Research by Akin et al. (2026) found that 159 children aged 8 to 11 years mostly made consecutive errors, showed smaller post-error slowing than 40 adults, and displayed higher error-related activity in the dorsal anterior cingulate cortex and anterior insula. Evidence from an electroencephalography study by Pietto et al. (2023) indicated that post-error slowing in preschool children was associated with post-error accuracy and frontal theta power, which suggests that adaptive adjustment emerges before formal schooling.

Cognitive control and numerical reasoning also depend on the maturation of white matter pathways that connect parietal, temporal, and frontal regions. According to the integrative model of Luna et al. (2015), cognitive control matures gradually across childhood and adolescence as brain systems change. Research by Buianova et al. (2025) examined the middle longitudinal fasciculus in 56 participants aged 10 to 29 years and reported linear relations between age and left fractional anisotropy and right radial diffusivity. A diffusion imaging study by Ayyıldız et al. (2023) compared 10 children with developmental dyscalculia and 16 typically developing peers and found lower white matter coherence and shorter tracts in the left superior longitudinal or arcuate fasciculus and the left anterior thalamic radiation in the dyscalculia group.

Reasoning also requires the suppression of intuitive strategies that are misleading. According to the inhibitory-control theory of the reasoning brain proposed by Houdé and Borst (2015), correct reasoning frequently requires inhibiting an automatic but incorrect strategy. Research by López-Ramón et al. (2026) tested a multidimensional model of inhibition in 313 individuals aged 17 to 20 years and reported that response inhibition efficiency was related to visuospatial working memory, whereas perceptual inhibition showed no such relation in the reported results. Because that sample consisted of young adults, evidence on whether the same pattern applies to children aged 7 to 12 years remains limited.

Interventions that target executive functions have attracted attention, and the evidence on their transfer to academic outcomes requires careful reading. A review by Gobet and Sala (2023) concluded that recent meta-analyses show a null overall effect of far transfer from cognitive training and recommended that research effort be redirected toward near transfer. In contrast, a three-level meta-analysis by Wei et al. (2024) reported that physical activity can enhance executive function in young children, with intervention duration acting as a moderator. Guided play, described by Weisberg et al. (2013) as a pedagogy that connects curricular goals with playful activity, was examined in a meta-analysis by Skene et al. (2022), which reported advantages over direct instruction for early mathematics ($g = 0.24$), shape knowledge ($g = 0.63$), and task switching ($g = 0.40$) among children aged 1 to 8 years.

The biological condition of the learner may also shape cognitive readiness during the school day. A longitudinal study by Yang et al. (2022), using data from 8,323 children aged 9 to 10 years in the Adolescent Brain Cognitive Development study, compared sufficient and insufficient sleep with a 9 hour cutoff and reported long-lasting associations with neurocognitive development over two years. Research by Jankowski et al. (2023) found that morning-type secondary school students performed better on crystallized intelligence tests in morning classes and showed no difference in afternoon classes. A systematic review by Biller et al. (2022) concluded that evidence on school start times and academic achievement does not yet show a general effect that extends beyond individual studies.

Taken together, existing studies have primarily examined error monitoring, white matter, inhibition, transfer, and biological rhythms in separate lines of work, and these lines often differ in age range, design, and measurement. Evidence on error monitoring has mainly come from behavioral and imaging tasks, and its connection with numerical reasoning in classroom contexts remains underexplored. Research on white matter pathways has relied on small samples or wide age ranges, research on inhibition has included young adult samples, and research on biological rhythms has partly involved adolescents, which limits direct inference for children aged 7 to 12 years. A review by Torrijos-Muelas et al. (2021) further reported that neuromyths persist among educators, which reinforces the need for classroom recommendations that rest on evidence synthesized with transparent methods.

This study addresses an underexplored aspect of educational neuroscience by integrating evidence on error monitoring, white matter pathways, multidimensional inhibition, domain context, and daily biological rhythms for children aged 7 to 12 years. This study extends previous research by examining these components together through a systematic review guided by PRISMA 2020 within the context of middle childhood. The aim of this study is to synthesize neuroscience and cognitive evidence published between 2020 and 2026 in order to examine whether and how these components support abstract reasoning in middle childhood. The contribution of this study is a neuropedagogical framework that combines immediate feedback, guided play, active breaks, domain-embedded practice, and rhythm-aware scheduling, and the framework is presented as a set of hypotheses for empirical testing.

This review is guided by four research questions: 1) How are error-monitoring circuits and white matter pathways related to abstract reasoning and numerical performance in children aged 7 to 12 years? 2) How is the architecture of multidimensional inhibition related to visuospatial working memory? 3) To what extent does domain context shape the outcomes of executive function interventions? 4) How are daily biological rhythms, physical activity, and guided play related to cognitive readiness for classroom learning?

METHODS

Review Design and Reporting Framework

This study is a systematic literature review that follows the PRISMA 2020 statement and its explanation and elaboration document, as published by Page et al. (2021). The statement guides transparent reporting of identification, screening, eligibility, and inclusion, and it was applied to the entire selection process. The four research questions stated at the end of the Introduction directed every stage of the search, and the elements of Population, Intervention or Exposure, Comparison, Outcomes, and Study design (PICOS) were defined before searching began. Table 1 presents the PICOS framework that structured the review questions and the eligibility decisions.

Table 1. PICOS Framework of the Systematic Review

Component	Description
Population (P)	Children aged 7 to 12 years (middle childhood) in a phase of cognitive transition
Intervention/Exposure (I)	Abstract reasoning processes, executive function interventions, guided play, and structured physical activity
Comparison (C)	Conventional direct instruction or no-intervention control groups, where applicable
Outcomes (O)	Neural activity (fMRI, DTI, EEG), error-monitoring efficiency, visuospatial working memory capacity, and academic accuracy
Study design (S)	Peer-reviewed experimental neuroscience studies, fMRI or DTI studies, empirical intervention research, and meta-analyses or systematic reviews that summarize such evidence

Table 1 shows that population, exposure, comparison, outcome, and design were defined explicitly before the search began.

Search Strategy and Eligibility Criteria

The search was conducted from January to March 2026 in Scopus, Web of Science, and PubMed, and it covered records published from 2020 to 2026. Keywords were combined with Boolean operators to capture the constructs of educational neuroscience, executive function, abstract reasoning, middle childhood, and neuroimaging. Selection proceeded in stages, beginning with removal of duplicates, followed by title and abstract screening, and ending with full-text assessment. Table 2 presents the search string together with the inclusion and exclusion criteria.

Table 2. Search Strategy and Eligibility Criteria

Aspect	Description
Databases	Scopus, Web of Science, PubMed
Publication period	2020 to 2026
Search string	(“Educational Neuroscience” OR “Neuropedagogy” OR “Cognitive Neuroscience”) AND (“Executive Function” OR “Inhibitory Control” OR “Working Memory”) AND (“Abstract Reasoning” OR “Cognitive Transition”) AND (“Primary School” OR “Elementary Education” OR “Middle Childhood”) AND (“fMRI” OR “DTI” OR “dACC” OR “White Matter”)
Inclusion criteria	Peer-reviewed journal articles indexed in Scopus or Web of Science; empirical neuroscience data, cognitive intervention data, or meta-analyses of such data; participants aged 7 to 12 years or in the transition from preschool to primary school; clear measurement; written in English or Indonesian
Exclusion criteria	Articles without peer review, opinion pieces, editorials, short conference reports, studies with mainly adult or animal samples without relevance to children, and studies focused on severe clinical pathology

Table 2 shows that the search string combined five concept blocks and that eligibility was restricted to peer-reviewed empirical or meta-analytic evidence.

Review Workflow

The review procedure followed six sequential stages that moved from question formulation to framework development. Each stage produced an output that was used by the next stage, and these outputs were documented to keep the process traceable.

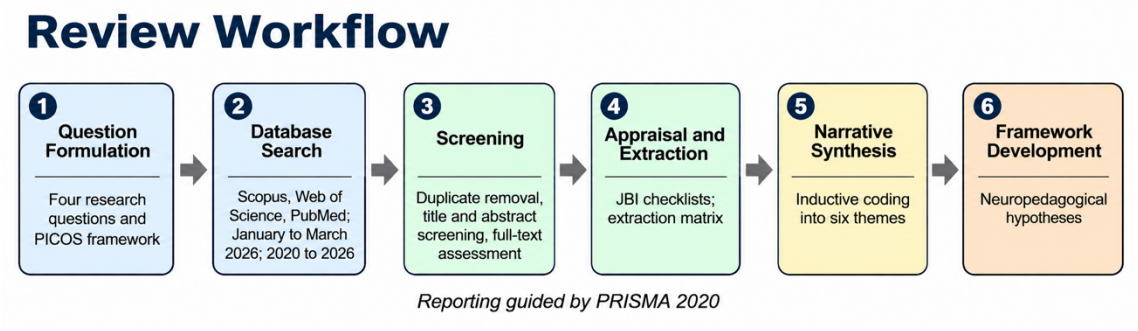


Figure 1. Workflow of the Systematic Review

Figure 1 shows that the review proceeded from questions to evidence and from evidence to a testable framework.

Quality Appraisal, Data Extraction, and Synthesis

All 23 final articles were appraised with the Joanna Briggs Institute critical appraisal checklists, in line with the revised tools described by Barker et al. (2023). The appraisal considered the clarity of the design, the validity of the measurement, the adequacy of the sample, and the appropriateness of the analysis. Data extraction recorded author identity, publication year, sample size and characteristics, neuroscience method, executive function component measured, and key findings. These fields were entered into an extraction matrix that supported the construction of Tables 4 to 6.

Data were synthesized through integrative narrative synthesis, because the included studies differed in design, age range, and outcome measures. Recurring findings were grouped inductively into themes, and each theme received a short code so that every finding could be traced to its source study. The six themes were error monitoring, white matter pathways, multidimensional inhibition, domain context and transfer, daily biological rhythms, and physical activity and guided play. Interpretations were limited to what the extracted findings supported, and evidence from adolescents or young adults was labeled as comparison evidence.

RESULTS

Study Selection

The database search and the selection stages produced the record counts that are summarized in Table 3. The table lists identification, screening, eligibility, and inclusion in the sequence recommended by PRISMA 2020. It also reports the reasons for exclusion at the screening and eligibility stages.

Table 3. Number of Records at Each Stage of PRISMA 2020 Selection

Stage	Description	Number
Identification	Records from Scopus (220), Web of Science (165), and PubMed (100)	485
	Duplicate records removed	120
Screening	Records screened by title and abstract	365
	Records excluded (no brain or executive function focus, n = 180; not the target child population, n = 110)	290
Eligibility	Full-text reports assessed	75
	Reports excluded (age mismatch, n = 22; incomplete data, n = 18; outside the context of primary education, n = 12)	52
Included	Studies in the synthesis	23

Table 3 shows that 23 of 485 records, or 4.7%, reached the final synthesis. The largest reductions occurred at the duplicate removal and title and abstract screening stages, which indicates that the search string captured a broad set of records before the criteria narrowed it.

Figure 2 presents the same selection process as a PRISMA 2020 flow diagram. The diagram follows the standard layout that can be generated with the tool described by Haddaway et al. (2022) for PRISMA 2020 compliant flow diagrams. It displays the flow of records from identification to inclusion and shows the number and reason of each exclusion.

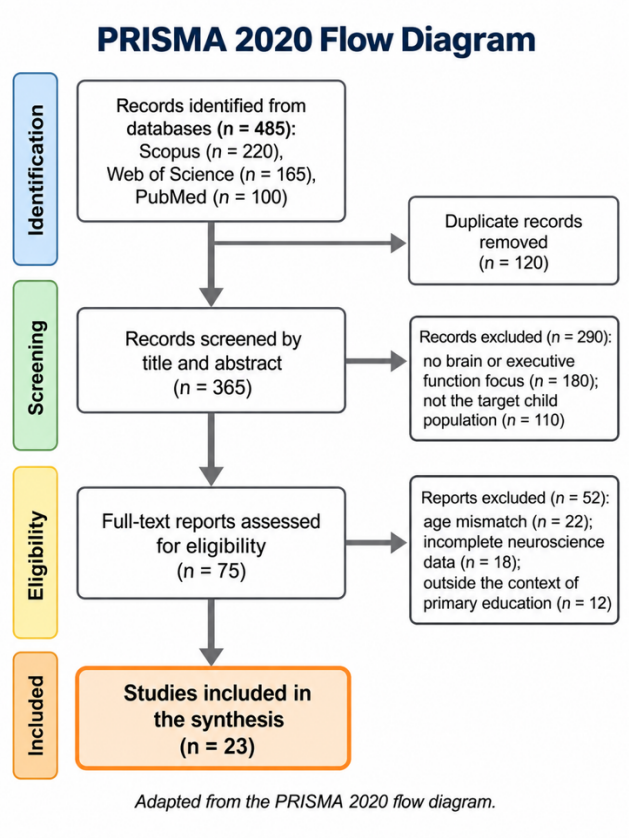


Figure 2. PRISMA 2020 Flow Diagram of Study Selection

Figure 2 confirms that every exclusion was accompanied by a counted reason.

Thematic Synthesis and Coding

Narrative synthesis of the included studies produced six themes, and each theme was assigned short codes for its findings. Table 4 presents the themes, the codes, the core findings, and the interpretation for learning. The matrix links neuroscience evidence with classroom meaning in one view.

Table 4. Matrix of Themes, Codes, Core Findings, and Interpretation for Learning

Theme	Codes	Core findings	Interpretation for learning
A. Error monitoring	PG-1 to PG-6	Consecutive errors were dominant in children; post-error slowing was smaller than in adults in one task-switching study; dACC and anterior insula activity was high; adaptive adjustment was already present in preschool and early school years	Immediate feedback and guided correction match the maturity of the circuit

B. White matter pathways	SA-1 to SA-4	MdLF showed a linear relation with age and diffusivity asymmetry; left-pathway coherence was lower in developmental dyscalculia	Abstraction demands should increase in steps because pathway maturation differs between children
C. Multidimensional inhibition	IM-1 to IM-3	Response inhibition was related to visuospatial working memory; perceptual and response inhibition appeared independent; inhibition-academic relations varied by skill	Thinking pauses and instructions divided into small steps may protect working memory
D. Domain context and transfer	KD-1 to KD-4	Executive function-academic relations were significant but weaker after general executive function was accounted for; far transfer was null overall; physical activity combined with instruction benefited mathematics	Control practice should be embedded in subject content
E. Daily biological rhythms	RB-1 to RB-4	Insufficient sleep was associated with neurocognitive differences; chronotype and class time mattered for crystallized intelligence; no general effect of school start time was shown	Rhythm-aware scheduling should be tested locally before it becomes policy
F. Physical activity and guided play	PP-1 to PP-5	Physical activity improved executive function with duration as moderator; effects were clearest for updating and shifting; benefits for working memory were selective; guided play showed advantages	Active breaks and guided play can serve as conditions of learning readiness

Table 4 shows that the six themes extend from neural circuits to classroom practice. The interpretation column benefits teachers and curriculum designers because it translates technical findings into possible instructional adjustments.

Theme A: Error Monitoring (PG)

Research by Akin et al. (2026) reported that children aged 8 to 11 years (n = 159) mostly made consecutive errors and that adults (n = 40) mostly made isolated errors (PG-1), and that post-error slowing was larger in adults (PG-2). In the scanned subsample (n = 72), children showed high error-related activity in the dorsal anterior cingulate cortex and anterior insula, and insula activity was related to better performance and smaller switch costs (PG-3). Research by Pietto et al. (2023) found in preschool children that post-error slowing was associated with post-error accuracy and frontal theta power (PG-4), and research by Dubravac et al. (2022) found that slowing on the first post-error trial declined across the ages of 8, 10, and 12 years and adulthood (PG-5). Research by Ger and Roebers (2023) found post-error slowing in children aged 4 to 6 years in two inhibition tasks (PG-6), and an interpretation consistent with these findings is that consecutive errors in the classroom may signal developing post-error adjustment that teachers can support with immediate feedback and guided correction.

Theme B: White Matter Pathways (SA)

Research by Buianova et al. (2025) examined the middle longitudinal fasciculus in 56 participants aged 10 to 29 years, including 22 children aged 10 to 13 years, and found group differences in mathematics performance and diffusivity measures (SA-1). The same study reported linear relations between age and left fractional anisotropy and right radial diffusivity (SA-2), and lower right than left middle longitudinal fasciculus diffusivity in all groups (SA-3). Research by Ayyıldız et al. (2023) reported lower white matter coherence and shorter tracts in the left superior longitudinal or arcuate fasciculus and the left anterior thalamic radiation in 10 children with developmental dyscalculia compared with 16 typically developing peers (SA-4). These results suggest that the middle longitudinal fasciculus and left-hemisphere pathways can serve as developmental markers, and that differences in pathway maturation between children call for graded steps in abstraction demands.

Theme C: Multidimensional Inhibition and Working Memory (IM)

Research by López-Ramón et al. (2026) tested relations among executive processes in 313 individuals aged 17 to 20 years and found that faster response inhibition was related to better visuospatial working memory (IM-1). Perceptual inhibition and response inhibition appeared independent of each other, and only response inhibition was related to working memory in the results reported by that study (IM-2). A meta-analysis by Spiegel et al. (2021) reported that the developmental trends in relations of inhibitory control and shifting with academic outcomes varied according to the academic skill examined (IM-3). Because the key inhibition study used young adults, these patterns serve as working hypotheses for children, which teachers and researchers can examine through thinking pauses and the division of instructions into small steps.

Theme D: Domain Context and the Limits of Transfer (KD)

The meta-analysis by Spiegel et al. (2021) reported that accounting for general executive function produced weaker relations between executive function and academic skills than bivariate relations, although all relations remained significant throughout elementary school (KD-1). The same meta-analysis found that working memory was consistently and moderately related to mathematics and that few developmental changes appeared in the relations between executive function components and mathematics (KD-2). A review by Gobet and Sala (2023) concluded that the overall far-transfer effect of cognitive training is null (KD-3), and evidence from 92 randomized trials analyzed by Vasilopoulos et al. (2023) showed no overall benefit of physical activity for academic outcomes, although physical activity combined with academic instruction for 6 to 10 weeks benefited mathematics (KD-4). An interpretation consistent with these findings is that control practice is most meaningful when it is embedded in subject matter tasks that require learners to inhibit an intuitive but misleading strategy, as described by Houdé and Borst (2015).

Theme E: Daily Biological Rhythms (RB)

Research by Yang et al. (2022) compared 4,142 children with sufficient sleep and 4,181 children with insufficient sleep, using a 9 hour cutoff, and reported long-lasting associations with neurocognitive development over two years (RB-1). Research by Jankowski et al. (2023) found that morning-type secondary school students performed better on crystallized intelligence tests in morning classes and showed no difference in afternoon classes (RB-2), and no synchrony effect appeared for fluid intelligence (RB-3). A systematic review by Biller et al. (2022) concluded that evidence on school start times and academic achievement does not yet show a general effect that extends beyond individual studies (RB-4). An interpretation consistent with these findings is that evidence for children aged 7 to 12 years remains limited and partly relies on adolescents, so rhythm-based scheduling needs to be tested in local contexts before it is considered as policy.

Theme F: Physical Activity and Guided Play (PP)

Research by Wei et al. (2024) showed through a three-level meta-analysis that physical activity enhanced executive function in young children, with intervention duration acting as a moderator (PP-1), and a review by Mao et al. (2024) examined cognitively engaging physical activity interventions in children and adolescents (PP-2). A meta-analysis by Song et al. (2022) of 11 articles (N = 2,053) in children aged 4 to 12 years reported an overall executive function effect of SMD = 0.21, with effects for updating (SMD = 0.17) and shifting (SMD = 0.32), and with sessions of 35 minutes or longer showing SMD = 0.30 (PP-3). Evidence from 92 randomized trials analyzed by Vasilopoulos et al. (2023) indicated small benefits for working memory (g = 0.18) and fluid intelligence (g = 0.16) and no overall benefit for attention, inhibitory control, planning, or cognitive flexibility, while aerobic activity of moderate to vigorous intensity benefited executive function outcomes in moderator analyses (PP-4). A meta-analysis by Skene et al. (2022) of 17 studies (N = 3,893) in children aged 1 to 8 years reported advantages of guided play over direct instruction for early mathematics (g = 0.24), shape knowledge (g = 0.63), and task switching (g = 0.40) (PP-5), which suggests that active breaks and guided play are worth designing as conditions for learning readiness with adjusted duration and cognitive demand.

Characteristics of Anchor Studies

Anchor studies are the studies that served as the main source of each theme code. Table 5 summarizes the design, sample, key findings, and codes of these studies. The table also identifies which studies provide comparison evidence from adolescents or young adults.

Table 5. Characteristics of Anchor Studies

Author (year)	Design and sample	Key findings	Code
Akin et al. (2026)	Behavioral and fMRI study; 159 children aged 8 to 11	Consecutive errors dominant in children; smaller post-error slowing;	PG-1 to PG-3

	years, 40 adults, fMRI subsample of 72 children	high dACC and anterior insula activity	
Pietto et al. (2023)	EEG, go/no-go task; preschool children	Post-error slowing related to post-error accuracy and frontal theta power	PG-4
Dubravac et al. (2022)	Two behavioral studies; children aged 8, 10, and 12 years and adults; Stroop, Simon, and flanker tasks	Post-error slowing in all age groups; slowing on the first post-error trial declined with age	PG-5
Ger and Roebers (2023)	Behavioral study; children aged 4 to 6 years; Funny Fruits task (n = 143) and Hearts and Flowers task (n = 170), 74 children on both	Post-error slowing in both tasks and in both blocks of Hearts and Flowers	PG-6
Buianova et al. (2025)	DTI; 56 participants aged 10 to 29 years (22 children)	Linear relations of age with left FA and right RD; lower right than left MdLF diffusivity	SA-1 to SA-3
Ayyıldız et al. (2023)	Diffusion imaging; 10 children with developmental dyscalculia and 16 typically developing children	Lower coherence and shorter tracts in left-hemisphere pathways	SA-4
López-Ramón et al. (2026)	Path analysis; 313 young adults aged 17 to 20 years (comparison evidence)	Response inhibition related to visuospatial working memory; perceptual inhibition not related	IM-1, IM-2
Spiegel et al. (2021)	Meta-analysis; 299 studies, 65,605 elementary school children	Relations between executive function and academic outcomes remained significant but were weaker after general executive function was accounted for; working memory consistently moderately related to mathematics	IM-3, KD-1, KD-2
Gobet and Sala (2023)	Review of meta-analyses on cognitive training	Overall far-transfer effect null; near transfer recommended	KD-3
Vasilopoulos et al. (2023)	Three-level meta-analysis; 92 randomized trials, N = 25,334, children aged 5 to 12 years	Small benefits for working memory and fluid intelligence; no overall benefit for academic outcomes; mathematics benefits when physical activity was combined with instruction	KD-4, PP-4
Wei et al. (2024)	Three-level meta-analysis; young children	Physical activity improved executive function; duration as moderator	PP-1
Mao et al. (2024)	Systematic review and meta-analysis of randomized trials; children and adolescents	Cognitively engaging physical activity examined in relation to executive function	PP-2
Song et al. (2022)	Meta-analysis; 11 articles, N = 2,053, children aged 4 to 12 years	Overall executive function SMD = 0.21; updating SMD = 0.17; shifting SMD = 0.32	PP-3
Skene et al. (2022)	Meta-analysis; 17 studies, N = 3,893, children aged 1 to 8 years	Guided play superior to direct instruction for early mathematics, shape knowledge, and task switching	PP-5

Yang et al. (2022)	Longitudinal propensity score matched cohort; 8,323 children aged 9 to 10 years; 2 year follow-up	Insufficient sleep associated with long-lasting neurocognitive differences	RB-1
Jankowski et al. (2023)	School-based study; secondary school students (comparison evidence)	Chronotype and class time synchrony for crystallized intelligence; no effect for fluid intelligence	RB-2, RB-3
Biller et al. (2022)	Systematic review; secondary school students (comparison evidence)	No general effect of school start time shown beyond individual studies	RB-4

Table 5 shows that most anchor studies involved children and that three studies provided comparison evidence from adolescents or young adults. The table also shows that several anchor studies are meta-analyses or reviews, which increases the breadth of evidence and reduces dependence on single small samples.

Integrative Synthesis

The six themes were integrated by linking each theme with a neurobiological mechanism, a pedagogical implication, and a note on the strength of evidence for children aged 7 to 12 years. Table 6 presents this integration. The strength-of-evidence notes were based on the availability of child samples, sample size, and the type of design in the anchor studies.

Table 6. Relations among Themes, Mechanisms, and Pedagogical Implications

Theme	**Neurobiological mechanism**	**Pedagogical implication**	**Evidence note for children aged 7 to 12 years**
Error monitoring	dACC and anterior insula circuits; post-error slowing	Immediate feedback; guided correction	Moderate; child studies are available
White matter pathways	MdLF; left superior longitudinal and arcuate fasciculus; left anterior thalamic radiation	Graded steps in abstraction	Limited; small samples and wide age ranges
Multidimensional inhibition	Response inhibition and visuospatial working memory	Thinking pauses; instructions in small steps	Limited; key study in young adults
Domain context	Executive control interacting with subject content	Practice embedded in lessons	Moderate; from reviews and meta-analyses
Daily biological rhythms	Sleep duration; chronotype and class time synchrony	Locally tested scheduling; sleep health education	Limited; partly from adolescents
Physical activity and guided play	Updating, shifting, and working memory demands in active tasks	Active breaks; guided play	Moderate; from meta-analyses

Table 6 shows that evidence is moderate for error monitoring, domain context, and physical activity with guided play, and limited for white matter pathways, inhibition, and biological rhythms.

Figure 3 summarizes the relations among the themes in one conceptual model. The model arranges biological conditions, cognitive control processes, and classroom strategies in layers that lead to abstract reasoning. The model is a synthesis of the reviewed evidence and is presented as a hypothesis for empirical testing.

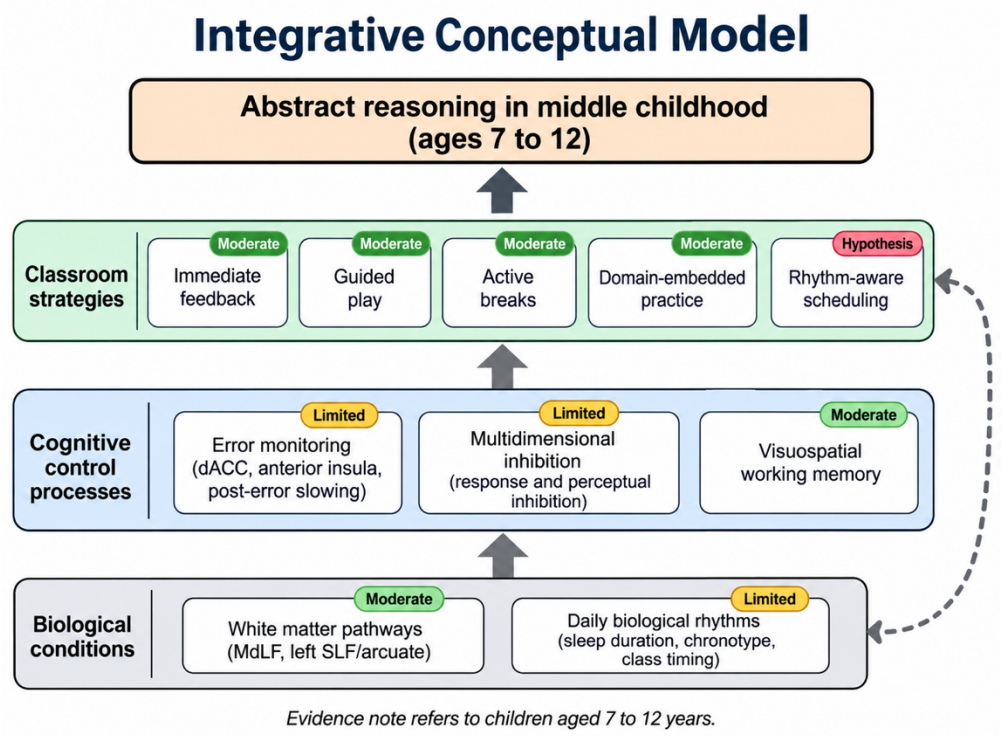


Figure 3. Integrative Conceptual Model of Abstract Reasoning in Middle Childhood

Figure 3 indicates that classroom strategies operate at the upper layer, whereas biological conditions form the base that shapes readiness.

DISCUSSION

Error Monitoring and Its Developmental Course

The synthesis indicates that children in middle childhood mostly made consecutive errors and showed smaller post-error slowing than adults in a task-switching paradigm, together with high error-related activity in the dorsal anterior cingulate cortex and anterior insula. A plausible explanation is that the error-monitoring system is already active but is still being calibrated, so that detection of an error does not always lead to efficient adjustment on the next trial. This explanation is consistent with the account of Botvinick et al. (2004), in which anterior cingulate monitoring signals the need for increased control, and with the review by Ullsperger et al. (2014) on performance monitoring and adaptive behavior. Research by Pietto et al. (2023) and by Ger and Roebers (2023) showed that post-error

adjustment is already present in preschool and early school years, which indicates that the system begins to operate before formal instruction.

Different patterns have been reported for the direction of age differences, because Dubravac et al. (2022) found that slowing on the first post-error trial declined with age whereas Akin et al. (2026) found larger post-error slowing in adults. This variation may be associated with differences in tasks, in the trials used to compute slowing, and in the age ranges compared, and the findings should be interpreted in relation to these differences. An interpretation that fits both patterns is that post-error behavior changes qualitatively with age, shifting from a strong orienting response toward errors to more balanced adjustments, as described by Dubravac et al. (2022). For classroom practice, this interpretation supports immediate feedback and guided correction as strategies that match children's developing adjustment, and it also calls for classroom studies that link error monitoring with numerical reasoning.

White Matter Pathways and Numerical Reasoning

The synthesis indicates that white matter microstructure of the middle longitudinal fasciculus is linearly related to age and that lower left-hemisphere pathway coherence accompanies developmental dyscalculia. These patterns may reflect the gradual maturation of long association pathways that connect regions involved in arithmetic, which Luna et al. (2015) place within a broader maturation of cognitive control. Research by Buianova et al. (2025) proposed that right-left-right hemispheric dominance, as described in a theory of cognitive development, may explain the observed patterns, and research by Ayyıldız et al. (2023) reported that lower coherence and shorter tracts tended to be associated with lower mathematics performance. Both studies used diffusion imaging in samples that differed in size and age range, which means that their findings complement each other without being directly equivalent.

The study by Buianova et al. (2025) reported lower diffusivity in the right than in the left tract in all age groups, and this finding should be interpreted in relation to the hemispheric dominance proposal that the authors raised. Other patterns in the left-hemisphere pathways were reported in dyscalculia, so mapping numerical pathways in children needs to include both hemispheres. Because the dyscalculia sample included only 10 children and the age range in the first study was wide, the findings are best treated as developmental markers that require replication. For instruction, the implication is that tasks should increase abstraction in graded steps because maturation of pathways differs between children, and any use of imaging findings in classrooms should be careful about overinterpretation.

Multidimensional Inhibition and Working Memory

The synthesis indicates that more efficient response inhibition was related to better visuospatial working memory in young adults and that perceptual inhibition and response inhibition appeared as separate processes. This pattern may arise because suppressing a prepotent response frees limited capacity for holding and manipulating spatial information, which fits the view of Diamond (2013) that inhibitory control and working

memory work together to support reasoning. It is also compatible with the inhibitory-control theory of Houdé and Borst (2015), in which correct reasoning often requires suppression of an intuitive strategy. The meta-analysis by Spiegel et al. (2021) provides complementary evidence from children, since the relations of inhibitory control with academic outcomes varied by academic skill and working memory was consistently related to mathematics.

The findings should be interpreted in relation to the age of the sample, because the key inhibition study involved participants aged 17 to 20 years and may not describe children aged 7 to 12 years. This variation may be associated with differences in the maturity of frontal control systems, and the framework of Miyake et al. (2000) suggests that inhibition is separable from other executive functions, which supports testing inhibition types separately in children. An interpretation that remains cautious is that thinking pauses and instructions divided into small steps may protect working memory during numerical tasks. The implication is a testable classroom hypothesis, and trials should compare these strategies with usual practice before they are recommended.

Domain Context and the Limits of Transfer

The synthesis indicates that executive function is related to academic outcomes throughout elementary school, whereas far transfer from executive function training is limited. A likely explanation is that gains from training remain tied to the trained task and context, so that general improvement appears only when practice shares features with the target skill. This view agrees with the conclusion of Gobet and Sala (2023) that far transfer is null overall and that research should turn to near transfer. It also agrees with the meta-analysis of Spiegel et al. (2021), which found weaker relations between executive function components and academic skills after general executive function was accounted for.

Evidence from physical activity trials adds nuance, because Vasilopoulos et al. (2023) found no overall benefit for academic outcomes but found benefits for mathematics when physical activity was combined with academic instruction. The variation between these results may be associated with the degree to which cognitive demand and subject content are integrated in the activity. An interpretation consistent with this evidence is that control practice is most useful when it is embedded in subject tasks that require inhibition of an intuitive strategy. For curriculum design, this implies that executive function practice should be built into lesson content, and the effect of such embedding should be tested for each subject.

Daily Biological Rhythms

The synthesis indicates that sleep duration and the timing of lessons were related to cognitive performance, although evidence for children aged 7 to 12 years remains limited. A possible explanation is that insufficient sleep affects the brain systems that support cognition, which is consistent with the longitudinal evidence of Yang et al. (2022) from more than 8,000 children aged 9 to 10 years. Research by Jankowski et al. (2023) found that the match between chronotype and class time mattered for crystallized intelligence

in secondary school students, and this result suggests that readiness may vary between children. A systematic review by Biller et al. (2022) did not identify a general effect of school start times, so the evidence base is heterogeneous.

Different patterns were reported for fluid intelligence, because Jankowski et al. (2023) found no synchrony effect for that construct. This variation may be associated with differences between the abilities measured and with the conditions of the school setting. The findings should be interpreted as indicating that rhythm-related readiness is a plausible factor, and the available studies do not allow firm claims about the best lesson time for children aged 7 to 12 years. The implication is that scheduling based on biological rhythms is a hypothesis for local pilot studies, and schools may consider sleep health education for families as a low-risk complement.

Physical Activity, Guided Play, and Implications for Neuropedagogical Practice

The synthesis indicates that cognitively engaging physical activity and guided play were associated with small to moderate benefits for executive function and for early mathematics. A plausible explanation is that these activities combine movement with decision making and rule following, which places demands on working memory, updating, and shifting. This explanation is consistent with the meta-analysis of Song et al. (2022), which found clear effects for updating and shifting, and with the three-level meta-analysis of Wei et al. (2024), which identified intervention duration as a moderator. The evidence from Vasilopoulos et al. (2023) shows a more selective pattern, with benefits for working memory and for aerobic activity of moderate to vigorous intensity, which indicates that the type of activity matters.

Differences in age coverage between meta-analyses call for caution, because Skene et al. (2022) included children aged 1 to 8 years and Mao et al. (2024) included children and adolescents, so generalization to ages 7 to 12 needs care. Guided play, as described by Weisberg et al. (2013), connects curricular goals with playful activity, and this link may explain why it supported early mathematics and task switching in the study of Skene et al. (2022). Four implications follow: immediate feedback and guided correction for error monitoring, guided play for the transition from concrete to abstract thinking, brief cognitively engaging active breaks, and rhythm-aware scheduling treated as a hypothesis. Caution is needed when neuroscience is translated into practice, because Torrijos-Muelas et al. (2021) reported that neuromyths persist among educators, and recommendations should therefore rest on evidence that has been tested in classrooms.

Limitations

The first limitation is that the review relies on secondary data from published literature, and no primary neuroscience data were collected from a local sample. The second limitation is heterogeneity of samples, because some anchor studies involved adolescents or young adults and others used wide age ranges, which limits generalization to children aged 7 to 12 years. The third limitation is the small sample size in some imaging studies, such as the 10 children in the dyscalculia group, and the fourth is the possibility of publication bias, since studies with significant results are more likely to be published.

Future research may test rhythm-based scheduling and active breaks through experimental designs with primary school students in Indonesia, and may examine the links between error monitoring and numerical reasoning with child samples.

CONCLUSION

This review concludes that abstract reasoning in middle childhood is supported by several interacting components, namely error-monitoring circuits, white matter pathways, multidimensional inhibition, and daily biological rhythms. Synthesis of 23 studies from 485 records indicated that children mostly made consecutive errors, that white matter maturation was related to mathematics performance, and that far transfer from executive function training was limited. Cognitively engaging physical activity and guided play showed small to moderate benefits, and evidence on sleep and class timing suggested that readiness may vary during the school day. These conclusions apply with different strength to each theme, because evidence for children aged 7 to 12 years was moderate for error monitoring, domain context, and physical activity with guided play and limited for white matter, inhibition, and biological rhythms.

The neuropedagogical framework combines immediate feedback, guided play, active breaks, and practice embedded in subject content. Rhythm-aware scheduling is positioned as a hypothesis that needs testing in local contexts. Experimental studies with primary school students are needed to test the framework, particularly for inhibition and biological rhythms. Such studies would indicate which components deserve inclusion in teacher education and curriculum development.

AI Use Statement

The authors used AI tools, if applicable, solely for language editing and proofreading. All authors take full responsibility for the content of this manuscript.

Author Contributions

JAFR: contributed to conceptualization, methodology, literature screening, data analysis, and manuscript drafting. DS: contributed to literature screening, data extraction, and thematic analysis. SMX: contributed to data interpretation and manuscript review. MN: contributed to the theoretical framework and critical review of the manuscript. DR: contributed to methodological review, interpretation of findings, and manuscript revision. AS: contributed to literature synthesis, manuscript drafting, and final editing. All authors reviewed and approved the final manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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