***Research Article*** *http://dx.doi.org/10.4314/mejs.v18i2.13* ***Open Access***

# The Cognitive-Metacognitive System in Learning: A Theoretical Framework with Examples in STEM Domains

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**ABSTRACT**

Metacognition helps educators develop and use better teaching and learning strategies, contexts, and materials. However, the development and use of such strategies, contexts, and materials require understanding how metacognition promotes the efficiency of the cognitive system. Therefore, this article aims to propose a cognitive–metacognitive system that illustrates how the metacognitive system enhances cognitive efficiency. To this end, publications by pioneering researchers in metacognition were retrieved and critically analyzed. Based on the analysis, we described the components and subcomponents of metacognition, elaborated the scheme of metacognitive control and monitoring, and proposed an outline of the operations of the cognitive–metacognitive system. The cognitive system performs activities to achieve cognitive goals, while the metacognitive system provides adaptive support that enhances its efficiency. The proposed cognitive-metacognitive system processes cognitive inputs (e.g., information, lessons, observations, problems, and tasks) and yields cognitive outputs (e.g., actions, artifacts, and behaviors) via a six-step sequence of mental activities, illustrated with examples from STEM education. The six-step framework indicates that (a) metacognitive awareness helps the cognitive system identify and deploy cognitive knowledge and strategies, and (b) metacognitive strategies regulate and enhance cognitive processing. The framework is believed to advance research and practice in STEM education and across educational domains.

**Keywords:** Cognitive-level model, Cognitive-metacognitive system, Mental models, Meta-level model, Metacognition components, Metacognitive control, Metacognitive monitoring.

## 1. INTRODUCTION

Metacognition is widely recognized as a critical tool for facilitating effective learning across disciplines and educational levels. Yet the implementation of metacognitive strategies in teaching and learning depends on a clear understanding of its components: an understanding that remains elusive despite decades of research. Scholars continue to debate its precise taxonomy, including its components, applications, and relationship to cognitive processes (Dennis and Somerville, 2023; Akturk and Sahin, 2011; Dinsmore et al., 2008; Veenman et al., 2006). While early frameworks such as Flavell's (1979) foundational distinction between metacognitive knowledge and experience provided direction, the need for unified and accessible models remains pressing. Numerous studies note that metacognitive theory is still



***Submitted: 21st February 2025 Accepted: 9th May2026 Published: 29th October 2026***



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difficult to translate into practical tools for educators and instructional designers (Zohar and Barzilai, 2013; Azevedo et al., 2010). Even after nearly five decades of research, the complexity of metacognition has not yet yielded straightforward classroom guidelines, leaving persistent gaps in instructional practice (Dennis and Somerville, 2023; Veenman, 2017; Efklides, 2011; Pintrich, 2002).

These long-standing concerns about the lack of consensus have repeatedly prompted calls for standardization, beginning with Veenman et al.'s (2006) appeal for a unified definition in the inaugural issue of *Metacognition and Learning*. Recent work continues to highlight the same challenge (Li, 2024; Ozturk, 2024; Azevedo, 2020; Bannister-Tyrrell et al., 2014; Tarricone, 2011). Debates also persist regarding the boundaries between cognitive and metacognitive constructs: for example, whether planning, declarative knowledge, or higher-order thinking skills should be conceptualized as cognitive processes or metacognitive strategies (Tran and Hasegawa, 2022; Winne, 2018; Krathwohl, 2002; Schraw and Moshman, 1995). Similarly, distinctions between metacognition and self-regulated learning, and between metacognitive knowledge and skills, remain contested (Dörrenbächer-Ulrich et al., 2024; Azevedo, 2020; Zohar and Barzilai, 2013; Veenman, 2005; Brown, 1987). This article, while establishing a clear understanding of the metacognition construct, its components, and its subcomponents, aims to provide a simplified framework of how the metacognitive and cognitive systems interact to facilitate learning. To this end, the review consults and studies several pioneering research articles in metacognition.

## 2. METHODS

The study was guided by formulating four key questions. (a) What are the components of metacognition? (b) How does the metacognitive system carry out control and monitoring to enhance learning? (c) How does the cognitive-metacognitive system operate to complete learning tasks? (d) How are the components of metacognition involved in improving the efficiency of cognitive processing? These questions helped us structure the article around three core topics: "components of metacognition," "control and monitoring in metacognition," and "operations of the cognitive-metacognitive system." The literature examined in this study consists primarily of publications by pioneering theorists in metacognition. The authors' familiarity with the field enabled the identification and retrieval of seminal works, many of which were already in the authors' possession. Recent studies attempting to develop unified frameworks, highlighting conceptual caveats, or stimulating debate were also included. Moreover, additional sources that support the propositions, before and after review of the

manuscript, were collected via an AI-assisted confirmatory literature search. Hence, the study proceeded as a conceptual synthesis guided by the four research questions, integrating the findings under the three core topics (Snyder, 2019; Torraco, 2005): producing an account that informs the proposed six-step cognitive-metacognitive framework and its pedagogical implications.

## 3. METACOGNITION AND ITS COMPONENTS

Metacognition, as it has been described by pioneer researchers in the subject (Flavell, 1979, 1976; Brown, 1987), constitutes knowledge (i.e., awareness) and regulation of one's own knowledge and thinking. Hence, the construct is commonly defined as the knowledge of one's own cognitive processes and the efficient use of that knowledge to self-regulate those processes (e.g., Shimamura, 2000; Brown, 1987). According to this definition, metacognition is viewed as a way of knowing about our cognitive processes and a way of deliberate and conscious regulation of such processes (Gordon and Braun, 1985). These components, i.e., "the way of knowing about our cognitive processes" and "the way of deliberate and conscious regulation of such processes," are widely referred to as *knowledge of cognition* and *regulation of cognition*, respectively (e.g., Schraw and Dennison, 1994; Allen and Armour-Thomas, 1991). Nonetheless, Flavell (1979, 1987) divided metacognition into metacognitive knowledge and metacognitive experience. According to him, metacognitive knowledge refers to one's knowledge about cognitive beings (agents), cognitive tasks, and cognitive strategies. Metacognitive experience refers to the conscious cognitive or affective experience that occurs during cognitive activity (Flavell, 1979). In his later work, John Flavell (1999) described metacognition as a construct that includes knowledge of cognition and executive skills (i.e., regulatory strategies). Thus, according to the well-established understanding, three components are apparent: metacognitive knowledge (i.e., knowledge of cognition), metacognitive regulation (often incorrectly conflated with self-regulation), and metacognitive experiences (e.g., Sbhatu, 2006; Pintrich, 2000). Metacognitive regulation (i.e., regulation of cognition) refers to metacognitive activities that help regulate one's thinking or learning (Schraw and Moshman, 1995).

Examining the lines of research in metacognition reveals the components more clearly. There are three fairly distinct lines of research in metacognition. Developmental, educational, and cognitive psychology researchers have been studying different aspects of the construct. They grounded their inquiry on distinct premises. Developmental psychology researchers study the development of metacognition in relation to various persons' variables:

such as age (van der Stel and Veenman, 2014; Weil et al., 2013; Kuhn, 2000; Brown, 1987; Flavell, 1987), novice versus expert (Paris, 2002; Schraw and Moshman, 1995), gifted versus non-gifted (Alexander and Schwanenflugel, 1996; Alexander et al., 1995), intelligence (Kolloff and Roebers, 2024; Veenman et al., 2002), and high versus low academic achievers (Hwang and Vrongistinos, 2002; Short, 1992). In this line of research, metacognition is treated as an object of study.

Educational psychology research, on the other hand, explores the roles of metacognition as a means or tool of self-regulated learning. Studies in this area examine the relationship between metacognition and academic achievement or performance (White and Frederiksen, 1998), transfer and retention of learned material (Sbhatu, 2006; Georghiades, 2000), problem-solving (Goos et al., 2002), and independent, self-regulated, or autonomous learning (Boekaerts, 1999; Victori and Lockhart, 1995). They also explore how metacognition is enhanced via instruction (Schraw, 2001). Finally, cognitive psychology researchers examine the basis and accuracy of metacognition in memory. The studies explore the roles of metacognitive experiences, as judgments and feelings, in monitoring cognitive states and subsequent control of cognitive processes (Efklides, 2002; Koriat and Shitzer-Reichert, 2002; Paris, 2002). They are narrowly confined to examining how cognitive processes are monitored and controlled.

Good use of metacognition as an effective tool in teaching and learning, via augmenting the cognitive system and complementing its limitations, depends on two principal requirements: (a) understanding the operations of the cognitive-metacognitive system and (b) knowledge of the functions of the components of metacognition. Therefore, elucidating the functions of the three components of metacognition in the operations of the cognitive-metacognitive system would assist teachers and instructional designers in selecting an ideal instructional context: one that would motivate learners to employ appropriate metacognitive knowledge and strategies in learning. The publications of John Flavell (1999, 1987, 1979, 1976) and of several contemporary and later scholars (e.g., Efklides, 2006, 2002; Krathwohl, 2002; Hartman, 2001; Koriat, 2000; Koriat and Levy-Sadot, 2000; Kuhn, 2000; Schraw and Moshman, 1995; Schraw and Dennison, 1994; Brown, 1987; Jacob and Paris, 1987) were instrumental in developing a comprehensive description of metacognition as provided below.

> Metacognitive knowledge constitutes individuals' knowledge (i.e., awareness) of what they know about: (a) themselves and others as cognitive processors: knowledge of person variables; (b) the nature of tasks and how they are processed: knowledge of task

variables; and (c) cognitive strategies: knowledge of strategy variables. Metacognitive regulation, on the other hand, refers to the regulation of cognitive processes and learning experiences by assisting the cognitive system in selecting and deploying a set of regulatory strategies and initiating regulatory activities: in the planning (preregulation), execution (intraregulation), and evaluation (postregulation) steps of the learning processes. Finally, metacognitive experiences refer to experiences that have something to do with the current or online cognitive endeavor: expressed as feelings (e.g., feelings of familiarity, knowing, difficulty, confidence, and satisfaction) and judgments (e.g., judgments of learning, solution correctness, task similarity, knowing, and performance). Metacognitive experiences can be information-based (i.e., analytic, task-related) and experience-based (i.e., heuristic, phenomenological).

Table 1 summarizes the components, subcomponents, and elements of metacognition. Descriptions are detailed in Annexure 1, with all definitions contextualized in relation to a cognitive task or activity.

*Table1. Components, Subcomponents, and Elements of Metacognition.*

| ***Components*** | ***Subcomponents*** | ***Elements*** |
|---|---|---|
| Knowledge | Knowledge of Cognitive Beings | Knowledge of Self as Cognitive Being |
| | | Knowledge of Others as Cognitive Beings |
| | | Knowledge of Homo sapiens as Cognitive Beings |
| | Knowledge of Cognitive Tasks | Knowledge of the Nature of Task |
| | | Knowledge of the Ways of Implementing Task |
| | | Knowledge of the Conditions for Implementing Task |
| | Knowledge of Cognitive Strategies | Knowledge of General Strategies |
| | | Knowledge of Specific Strategies |
| | | Knowledge of Effectiveness of Strategies |
| Regulation | Preregulation | — |
| | Intraregulation | Monitoring |
| | | Control |
| | Postregulation | — |
| Experience | Feelings | Feelings of Familiarity |
| | | Feelings of Knowing |
| | | Feelings of Difficulty |
| | | Feelings of Confidence |
| | | Feelings of Satisfaction |
| | Judgments | Judgments of Learning |
| | | Judgments of Solution Correctness |
| | | Judgments of Task Familiarity |
| | | Judgments of Knowing |
| | | Judgments of Performance |

## 4. CONTROL AND MONITORING IN METACOGNITION

The understanding of metacognition and its components guided us to articulate the proposed cognitive-metacognitive system and establish how it works. Nelson and Narens (1994)

postulated that the metacognitive system has two facets: knowledge objects and operations.

### 4.1. The Knowledge Facet

The knowledge facet represents meta-level mental models of people: of ongoing cognitive processes at the "object level." According to this model, "object-level" represents internal and external inputs or stimuli that trigger cognitive processing, including actions, activities, behaviours, cognitive processes, lessons, observations, problems, tasks, etc. In our framework, such inputs or stimuli are referred to as *cognitive inputs*. As can be noted in the descriptions of the "knowledge objects" of their framework, Nelson and Narens (1994) did not propose or imply object-level models. From the perspective of cognitive science, however, human cognition relies on internal mental models of the external world instead of directly accessing reality (Marr, 2010; Fodor, 1975). Our proposed framework, agreeing with the representationalism of cognitive science, suggests two types of mental models of cognitive inputs, namely *object-level* and *meta-level*. Here, there are some key questions worth posing. Does the above proposition signify that people represent cognitive input at two levels simultaneously? Are the meta-level models generated based on the object-level models, the cognitive inputs, or both?

The "object-level" representations are understood as mental models generated by the cognitive system alone, while the "meta-level" ones are understood as mental models produced by the cognitive system with the support of the metacognitive system. Hence, the "object-level" representations can be called *cognitive-level models*. Apparently, the cognitive-level and the meta-level models are representations of the same cognitive input, and their differences lie, the present authors contend, in their *quality*. While cognitive-level models are, relatively speaking, *simple*: lacking many details, the meta-level models are *elaborate*: bearing many details. Let us consider an example. If we give a 5-year-old child a "2 + 2" addition task, he may instantly represent the task as "2 eyes plus 2 ears," as commonly happens among young children. This one represents the simple, cognitive-level model. Since an answer of 4 is neither 4 eyes nor 4 ears, the child will be challenged to refine his model to something like "2 candies plus 2 candies," which represents an elaborate meta-level model. According to Nelson and Narens (1994), the meta-level models are referred to as *imperfect* models of the object-level processes.

### 4.2. The Operations Facet

Likewise, the operations facet is represented by two levels of dominance relations: "monitoring" and "control" (Winne, 1996; Nelson and Narens, 1994). It is a "cognitive-

executive process" where the monitoring and control actions of the meta-level system modify the object-level processing.According to this model, "control" is interpreted as a process where the meta-level system *modifies* the object-level processing but not vice versa (emphasis original).The meta-level system, which can be referred to as the cognitive-executive system, can change the state of the cognitive system or its processing. This change produces some kind of action in the cognitive system, including the initiation, continuation, or termination of a task. "Monitoring," on the other hand, is interpreted as the process where the meta-level system *is informed* by information flowing from the object-level processing, whereby the meta-level model of the situation is updated (emphasis original).Several influential studies have extended these postulates. However, certain contributions (e.g., Efklides et al., 2006; Nietfeld et al., 2006; Schraw, 2009) have broadened or redefined the constructs in ways that introduce conceptual ambiguity, making it difficult for educators and practitioners to apply the distinctions consistently.

With Nelson and Narens' (1994) model as background, it is helpful to provide distinctions between cognitive-level and meta-level models on the one hand and cognitive and metacognitive systems on the other. The distinctions help clarify how the control and monitoring systems of metacognition work, involving the systems and the mental models. According to cognitive science, a system with a monitoring role has a capacity for accessing all or part of the information regarding the entities it monitors (Newell, 1994; Norman and Shallice, 1986; Carver and Scheier, 1982). Hence, in the metacognitive monitoring process, the meta-level system should not be understood as "being informed" by object-level processing or its mental representation, as Nelson and Narens (1994) postulated. Rather, it must be understood as object-level processing, with its cognitive-level model "being accessed by" a metacognitive system, from which the meta-level model is generated. Similarly, the controlling role of metacognition should not be understood as "the meta-level directly modifying object-level processing," as articulated by Nelson and Narens (1994). Instead, it must be regarded as "the metacognitive system modifying the state and processing parameters of the cognitive system," which influences object-level processing (Eppinger et al., 2021; Lieder et al., 2018). Here, the existence of two distinct biological systems is not implied. It is rather being proposed that there are two functional systems with fairly distinct inputs, processing, and outputs, i.e., cognitive and metacognitive systems running within the same biological system of the brain. The two systems constitute the cognitive-metacognitive system, each of which can be referred to as a subsystem.

### 4.3. Monitoring and Control

In learners with well-developed metacognitive resources, the cognitive and metacognitive systems can operate concurrently, or the metacognitive system may remain inactive. When engaged, the metacognitive system provides *adaptive oversight* and *support* on demand, guiding cognitive task performance (Österholm et al., 2025; Zepeda and Nokes-Malach, 2023; van der Graaf et al., 2022; Dinsmore et al., 2008). If we begin with a cognitive input, where its processing requires the assistance of the metacognitive system, the following six mental processes occur, in sequence, within the cognitive-metacognitive system, as follows:

> First, the cognitive system develops a cognitive-level model of the input. Second, the metacognitive system accesses both the input and its cognitive-level model. In step three, the metacognitive system develops a meta-level model of the input. In stage four, the metacognitive system becomes aware of the input, one's cognitive capabilities, and the state of the input's processing (monitoring). In step five, the metacognitive system modifies the cognitive system (i.e., control). In the final step, the cognitive system processes the input to achieve a cognitive goal.

The output of monitoring consists of evaluative judgments about the meta-level model of a cognitive input and its ongoing processing. By contrast, the outputs of control include (a) cognitive strategies and tools used to process the input and (b) metacognitive strategies and tools employed to regulate that processing. Control processes are, thus, decisions generated on the basis of monitoring outputs (Schwartz and Perfect, 2002). By means of monitoring, learners observe and reflect on the nature of the cognitive activity and their own cognitive processes and receive information about the current state of cognition relative to their goals. The control system enhances the efficiency of the cognitive system by assisting in the selection and deployment of cognitive strategies in concert with metacognitive regulatory strategies.

Our proposition that the metacognitive system accesses the cognitive-level model of an input in order to monitor the cognitive processes leads us to suggest that it operates consciously. While some researchers argue that control processes may be conscious or unconscious (e.g., Schwartz and Perfect, 2002; Veenman et al., 2002), others provide justifications to show both monitoring and control as inherently conscious processes (e.g., Koriat and Shitzer-Reichert, 2002; Koriat, 2000). The present authors tentatively propose that, regardless of whether the cognitive system creates its cognitive-level model consciously or unconsciously, the metacognitive system must engage consciously to access and utilize that model (Rivas et al., 2022). Similarly, our proposition that the metacognitive system

controls cognitive-metacognitive operations by acting on the cognitive system, involving the selection and deployment of cognitive strategies to influence processes and their states, implies that control is either a conscious process or a subconscious one developed from past conscious experience. Recent studies in neuroscience strengthen this proposition (Saccenti et al., 2024; Boldt and Gilbert, 2022; Fleur et al., 2021).

### 4.4. Mental Representations

In addition to the philosophical framework of representationalism (Marr, 2010; Fodor, 1975), the idea that mental models serve as vehicles for organizing learning materials in cognitively manageable ways has been advanced not only within situated cognition but also across multiple theoretical frameworks associated with visualization (Mayer, 2005). According to the theory of situated learning, cognition is constituted by processes and outcomes of interactions between learners and their environment or context. Learners construct mental models of their physical and social environments to simulate relevant aspects of the situations to be learned (Seel, 2001; Greeno, 1998; Lave and Wenger, 1991; Norman, 1983). In this regard, Seel (2001) stated that "… in cognitive psychology and … educational psychology, mental models are considered qualitative mental representations … developed by learners based on their available world knowledge: aiming at solving problems or acquiring competence in a specific domain" (p. 407). Research on visualization, from static diagrams to immersive virtual reality, demonstrates that learning gains depend on the construction and progressive elaboration of mental models (Abdulla and Sbhatu, 2026; Rexigel et al., 2024; Tene et al., 2024; Mayer, 2005), thereby supporting our distinction between initial cognitive-level representations and later, metacognitively supported meta-level representations.

## 5. OPERATIONS OF COGNITIVE-METACOGNITIVE SYSTEM

Establishing a clear interplay of the cognitive and metacognitive systems toward developing learning contexts that promote learning and instruction is the interest of educators. The cognitive system is a system that, via processes and strategies, performs cognitive activities like knowing, understanding, applying, analyzing, synthesizing, and evaluating (Arslan et al., 2023; Lintern, 2007). As indicated above, the inputs of the cognitive system can be data, information, lessons, observations, problems, tasks, etc., and its outputs are actions, artifacts, and behaviors (i.e., cognitive goals). Affective factors influence the efficiency of the activities of the cognitive system by affecting its processes and strategies (e.g., Schutz and Pekrun, 2007; Pekrun, 2006). On the other hand, the metacognitive system is a system that,

via its knowledge, strategies, and experiences, performs activities toward enhancing the efficiency of the cognitive system. While cognitive inputs, and their corresponding cognitive-level models, serve as inputs to the metacognitive system, its outputs are (a) meta-level models representing the state of the cognitive system, (b) the cognitive strategies selected and deployed to carry out cognitive processes, and (c) the metacognitive regulatory strategies that accompany and guide those processes. Cognitive-level models are mental representations created by mental processes, namely, memorizing, thinking, learning, and reasoning, using prior knowledge, problem-solving, and information processing. Meta-level models are generated by the same underlying mental processes, but they incorporate additional variables, such as features of the input, the cognitive strategies and one's capacity required to process it, and one's feelings, evaluations, and judgments about the processing and its outcomes. Three examples from STEM (science, technology, engineering, and mathematics) education are presented below to demonstrate the operations of the cognitive-metacognitive system.

### 5.1. Sorting Plants: An Example of Science Problem-Solving

Let us consider this problem-solving task, sorting plants of a given school compound into groups, to see the operations of the cognitive-metacognitive system and the roles of the three components of metacognition in enhancing the cognitive processes. The task, sorting plants of a given school compound into groups, is a cognitive input. Whether the task is given to a primary school child or a seasoned plant taxonomist, the learning process passes through six steps to achieve the cognitive goal. In other words, the operations of the cognitive-metacognitive system pass via six steps to help learners achieve a cognitive goal *effectively* (Sbhatu, 2023). The steps are given below and schematically in figure 1.

Step 1: *Cognitive-Level Model of the Task*: Learners (thinkers) generate a model of the task at hand at the cognitive level.

Step 2: *Metacognitive Awareness of the Cognitive-Level Model of the Task*: The metacognitive system accesses the cognitive-level model of the task.

Step 3: *Meta-Level Model of the Task*: Learners' metacognitive knowledge, feelings, and judgments are applied to generate a meta-level model of the [accessed] cognitive-level model of the task.

Step 4: *Metacognitive Awareness of Task, Cognitive Faculties, and Processes*: The meta-level model helps learners be aware of the features of the task, their cognitive faculties, and the states of their cognitive processing to solve it.

Step 5: *Selection and Deployment of Cognitive Strategies*: Learners employ metacognitive knowledge, judgments, and feelings to help them (i.e., their cognitive system) select and deploy cognitive strategies to carry out the task.

Step 6: *Execution of the Task to Achieve Cognitive Goal*: Learners carry out the task, supported by metacognitive regulatory strategies, while demonstrating the expected behavior, performing the correct action, and producing the required result, i.e., cognitive goal.

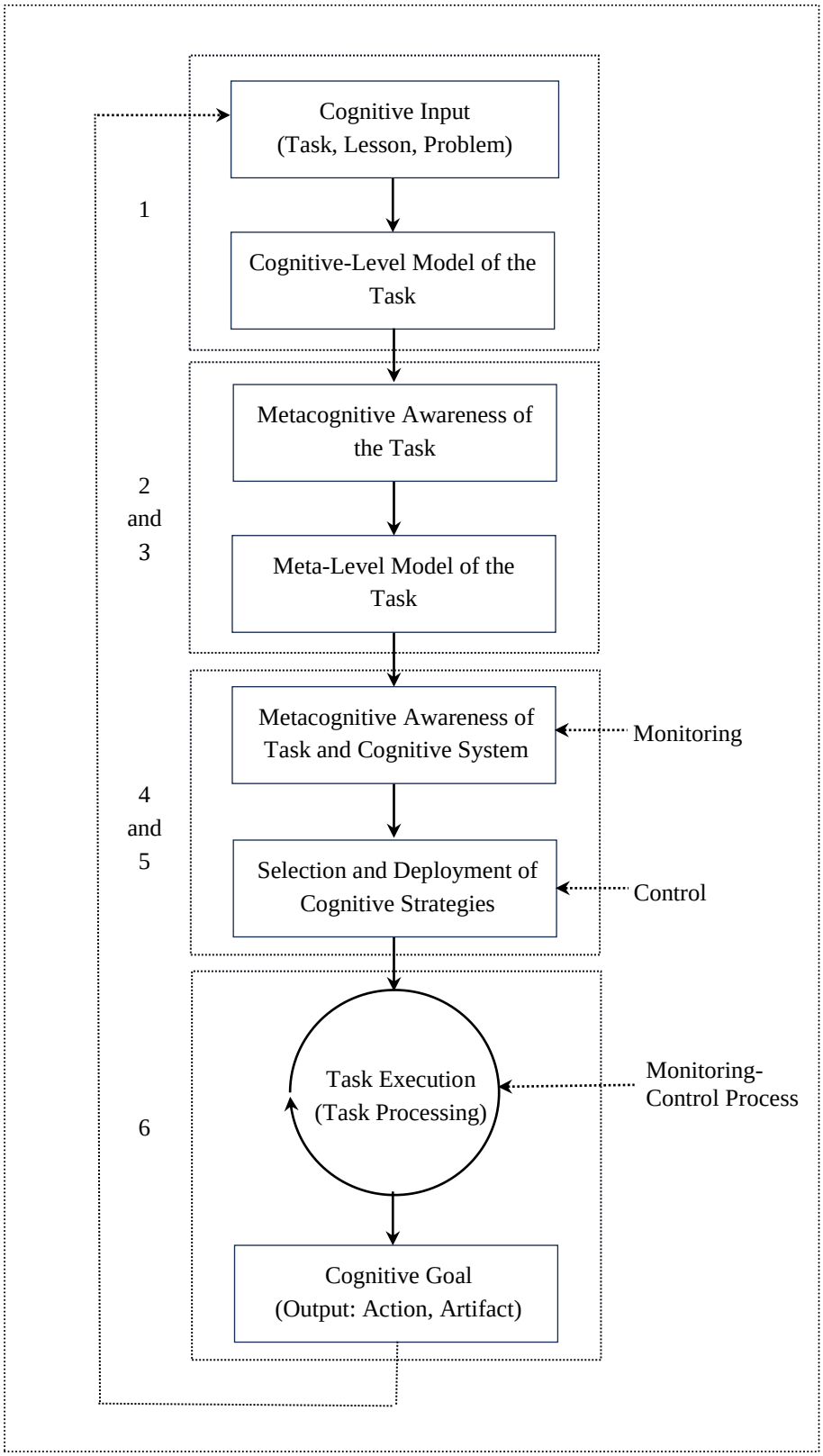



*Figure 1. Graphic Representation of the Operations of the Cognitive-Metacognitive System.*

The cognitive-level model of the task would involve grouping of the plants as "All Plants = Group A + Group B + … + Group X," and the meta-level model would involve

grouping of the plants as "All Plants + Criterion α = Group α1 + Group α2 + … + Group αn; All Plants + Criterion β = Group β1 + Group β2 + … + Group βn; or All Plants + Criterion δ = Group δ1 + Group δ2 + … + Group δn," where α, β, and δ could represent vegetative structure, vascular tissue, and leaf arrangement, respectively. In this task, "grouping" is the activity that leads to the development of mental models. A cognitive-level model is a "grouping of plants." However, the grouping becomes meaningful when some criterion is employed. The metacognitive system accesses the cognitive-level model and applies metacognitive knowledge, feelings, and judgments to generate a meta-level model. A meta-level mode shall, thus, be a "criterion-based grouping of plants". In this regard, unlike the simple cognitive-level model, the elaborate meta-level model makes the learner aware of the possibility of having several groupings based on various criteria. Vascular tissues, vegetative structures, and flower structures can serve as criteria. At this step, the learners become aware of the characteristics of the task, their own cognitive faculties, and the state of their cognitive processing. This awareness helps them deploy effective cognitive strategies, assisted by their metacognitive knowledge, judgments, and feelings, to complete the task. Metacognitive regulatory strategies are employed to assist the cognitive system in identifying and using appropriate strategies and tools in the course of processing the task: i.e., during the planning, execution, and evaluation stages.

**5.2. Reading "A Briefer History of Time for Understanding": Science Reading Example**

It is also helpful to consider a second example with a reading task and examine how the cognitive-metacognitive system functions. For this purpose, let us consider reading Stephen Hawking's "A Briefer History of Time" for understanding. "Reading A Briefer History of Time for understanding" constitutes a cognitive input: i.e., a reading task. It could be given to a theoretical physicist or a general booklover. In this task, "reading" leads to the development of mental models. Whereas "reading the book to understand its content" constitutes the cognitive-level model, "reading the book by using higher-order thinking (HOT) skills to understand its content" represents the meta-level model. The metacognitive system accesses the cognitive-level model. Then it applies metacognitive knowledge, feelings, and judgments and generates a meta-level model: i.e., "HOT skills-assisted reading of A Briefer History of Time."The meta-level model makes the reader aware that understanding of the text shall require the use of HOT skills, including application of prior knowledge, concept mapping, summarizing, analyzing, synthesizing, evaluating, inference, prediction, and hypothesis (Guterman, 2002; Gourgey, 1999; Glynn and Muth, 1994).

HOT skills, also referred to as critical thinking skills, are often treated both as cognitive (Dwyer et al., 2012) and as metacognitive skills (Xie et al., 2023; Joshi et al., 2022; Knight et al., 2022). In this work, we make a distinction between the two constructs. Learners' reflective abilities, experiences, knowledge, and skills in recognizing and selecting appropriate HOT skills are metacognitive. Conversely, such capabilities in applying the HOT skills to process learning material, as well as the HOT skills themselves, are cognitive. Readers, therefore, carry out the reading task by applying HOT skills, where metacognitive knowledge, judgments, and feelings are employed to assist the cognitive system in identifying and deploying appropriate HOT skills. In the course of reading, metacognitive regulation will be employed to assist the cognitive system in identifying and deploying sets of regulatory strategies and activities during the planning (pre-reading), monitoring (while reading), and evaluation (post-reading) stages (Kolić-Vehovec and Bajšanski, 2006; Sbhatu, 2006; Pressley and Afflerbach, 1995; Baker and Brown, 1984).

**5.3. Solving Linear Equation: An Example from Mathematical Problem-Solving**

Finally, let us consider a third example from mathematical problem-solving on the linear equation: compute $3x + 2 = 5$. "Computing $3x + 2 = 5$" is a cognitive input (i.e., a mathematical task or problem). In this case, "computing" is the task that leads us to the development of mental representations. "Computing $3x + 2 = 5$" constitutes a cognitive-level model, while "algebraic properties-assisted computing of $3x + 2 = 5$" is a meta-level one. The metacognitive system accesses the cognitive-level model. Then, it applies metacognitive knowledge, feelings, and judgments and generates an elaborate meta-level model: "algebraic properties-assisted computing of $3x + 2 = 5$." The meta-level model helps the learner be aware that solving the problem requires the application of algebraic properties, including (a) the property of additive inverse ($3x + 2 (– 2) = 5 + (– 2)$), (b) the property of zero ($3x = 3$), (c) the property of multiplicative inverse ($⅓(3x) = ⅓(3)$), and (d) the property of one ($1x = 1$, then $x = 1$). Problem-solvers, therefore, carry out the task assisted by their metacognitive knowledge, judgments, and feelings in selecting and deploying appropriate mathematical formulas and propositions. In solving an equation such as $3x + 2 = 5$, learners engage metacognitive regulatory strategies throughout the task: during planning, by identifying appropriate approaches, tools, and resources; during execution, by determining what is known and unknown, carrying out the required computations, and monitoring the process; and during evaluation, by verifying the accuracy and coherence of the obtained solution (Goos, 2002; Goos et al., 2002; Artzt and Armour-Thomas, 1992; Schoenfeld, 1987).

### 5.4. Elaborating the Cognitive-Metacognitive System

When the cognitive–metacognitive system operates to facilitate learning or knowing, it is regulated by the monitoring and control components of metacognition (Nelson and Narens, 1994; Flavell, 1979). During task engagement, the metacognitive system accesses cognitive-level models in Step 2 and generates meta-level models in Step 3. These meta-level models support learners' awareness of the task, their cognitive faculties, and ongoing processes in Step 4 (metacognitive monitoring), which in turn elicits the control system to take command (Pintrich, 2002; Schraw and Moshman, 1995). The control system, endowed with information produced through monitoring, assists in selecting and deploying cognitive strategies in Step 5 (Zimmerman and Moylan, 2009; Zimmerman, 2000; Winne and Hadwin, 1998). In the monitoring process, metacognitive knowledge, feelings, and judgments support the cognitive system (Veenman et al., 2006; Flavell, 1979). When these judgments and feelings are drawn upon during control, they influence the choice of cognitive strategies (Efklides, 2006; Schraw and Moshman, 1995). In Step 6, where the selected cognitive strategies are executed, metacognition continues to regulate performance through monitoring and control toward task completion (Sbhatu, 2023; Pintrich, 2000; Winne and Hadwin, 1998; Nelson and Narens, 1994).

The operation of the cognitive–metacognitive system is inherently linear. When learners fail to achieve their cognitive goal in Step 6, the system may reinitiate processing at Step 1; however, this repetition reflects the re-execution of an otherwise linear sequence, not a cyclical process. A genuinely cyclical system requires a built-in, obligatory feedback loop. In our framework, returning to Step 1 is conditional rather than structural. Even the monitoring-and-control facet of metacognition, often described as cyclical (e.g., Koriat and Shitzer-Reichert, 2002; Nelson and Narens, 1994), exhibits a loop only when tasks cannot be completed in a single pass. In such cases, ongoing checks may give the impression of a cycle, but this behavior is driven by task demands rather than a structural feedback mechanism. Thus, the system and its monitoring-and-control processes operate linearly, with repetition reflecting task-specific rework rather than an inherent cycle.

At this juncture, it is important to distinguish metacognitive monitoring of the cognitive–metacognitive system from the cognitive monitoring of task execution. The form of metacognitive monitoring described by Nelson and Narens (1994), and reconceptualized in this article, differs from the task-focused, task-based, and task-specific monitoring discussed in works such as Brown (1987); and Desoete (2008). Much of the literature has treated the

monitoring that occurs during task performance as inherently metacognitive (e.g., Nietfeld et al., 2006; Pieschl, 2009). Likewise, activities such as planning a task, monitoring its execution, and evaluating its outcomes are often labeled metacognitive (e.g., Desoete, 2008). However, these activities are fundamentally cognitive when they concern task-specific goals, steps, and outcomes rather than the learner's own cognitive operations (Manlove et al., 2007). What is genuinely metacognitive in these contexts is: (a) the awareness of task characteristics and of one's cognitive capacities (metacognitive knowledge), and (b) the selection and deployment of strategies based on that awareness (metacognitive regulation) (Schraw and Moshman, 1995; Brown, 1987; Flavell, 1979).

## 6. CONCLUSION

The proposed six-step framework delineates how the cognitive–metacognitive system functions as an integrated architecture. It shows not only where the three components of metacognition come into play but also how monitoring and control operate in real time to support cognitive work. More importantly, the framework makes visible what has often remained implicit in prior accounts: *the centrality of meta-level model generation* as the driver of effective regulation. According to this framework, the metacognitive system augments the cognitive system via (a) constructing meta-level models that enrich and reorganize the cognitive inputs; (b) selecting and deploying strategies and tools for processing the inputs; and (c) initiating regulatory activities that guide their execution across the six steps. While previous metacognition research has thoroughly documented the role of strategic and regulatory processes, far less attention has been paid to the quality of the meta-level representations that make such regulation possible. This framework brings that overlooked element forward.

This article illustrates how the cognitive and metacognitive systems work together to process cognitive inputs and reach a learning goal. It argues that the system's effectiveness depends first on the learner's capacity to generate sufficiently elaborate meta-level models and next on the strategic knowledge required to process and regulate the task. Where such models are thin or absent, regulation weakens; where they are rich, both cognitive processing and metacognitive oversight improve. Accordingly, practitioners aiming to integrate metacognition into instruction should help learners develop three capacities: (a) generating detailed meta-level models of cognitive inputs, (b) identifying and deploying appropriate cognitive strategies and tools, and (c) selecting and initiating regulatory strategies during planning, execution, and evaluation. These skills must be cultivated across educational levels

and disciplines if metacognition is to yield its intended benefits. Future empirical work should examine the validity and effectiveness of these propositions across domains, developmental stages, and cultural contexts.

## 7. ACKNOWLEDGEMENTS

The authors thank the Scholars Rescue Fund of the International Institute of Education (SRF-IIF) for granting a fellowship to Dr. Desta Berhe Sbhatu and the UiTM for hosting him during the final preparation of this manuscript. The authors are also thankful for Dr. Hailu Nigus Weldeana for his support in articulating the Solving Linear Equation example included in the manuscript.

## 8. CONFLICT OF INTERESTS

There are no conflicts of interests.

## 9. REFERENCE

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*Annexure 1. Descriptions of the Components and Subcomponents of Metacognition and Descriptions.*

**1. Metacognitive Knowledge**

It refers to one's knowledge (awareness) of one's own knowledge regarding cognitive beings, cognitive tasks, and cognitive strategies. Based on Flavell's pioneering works (1979), metacognition knowledge can be organized as follows by having "cognitive task" as a reference.

**1.1. Knowledge of Cognitive Beings**: Refers to knowledge of one's knowledge of what s/he knows and believes about human beings as cognitive organisms. The type of metacognitive knowledge with respect to knowledge of cognitive beings is declarative metacognitive knowledge.

(a) *Knowledge of Self as Cognitive Being*: Knowledge of what one does and doesn't know and believe about one's own knowledge in relation to a cognitive task.

(b) *Knowledge of Others as Cognitive Beings*: Knowledge of what one does and doesn't know and believe about one's own knowledge regarding someone's knowledge and belief in relation to a cognitive task.

(c) *Knowledge of* Homo sapiens *as Cognitive Beings*: Knowledge of what one does and doesn't know and believe about one's own knowledge regarding humans' knowledge and belief about a cognitive task.

**1.2. Knowledge of Cognitive Tasks**: Refers to knowledge of one's own knowledge about the nature of tasks, ways of processing the tasks, and conditions for processing them.

(a) *Knowledge of the Nature of Task*: Knowledge of what one does and doesn't know about one's own knowledge regarding the nature of a cognitive task. This is declarative metacognitive knowledge about a cognitive task.

(b) *Knowledge of the Ways of Implementing Task*: Knowledge of what one does and doesn't know about one's own knowledge regarding procedures and tools required and not required to carry out a cognitive task. This is procedural metacognitive knowledge about a cognitive task.

(c) *Knowledge of the Conditions for Implementing Task*: Knowledge of what one does and doesn't know about one's own knowledge regarding the conditions for implementing a cognitive task. Likewise, this is conditional metacognitive knowledge about a cognitive task.

**1.3. Knowledge of Cognitive Strategies**: Refers to knowledge of one's own knowledge of what one knows about learning, thinking, and problem-solving strategies.

(a) *Knowledge of General Strategies*: Knowledge of one's own knowledge about general cognitive strategies for carrying out a cognitive task and other similar tasks. The knowledge of general strategies can be declarative, procedural, and/or conditional metacognitive knowledge.

(b) *Knowledge of Specific Strategies*: Knowledge of one's own knowledge about specific cognitive strategies for carrying out a cognitive task. The knowledge of specific strategies is also declarative, procedural, and/or conditional metacognitive knowledge.

(c) *Knowledge of Effectiveness of Strategies*: Knowledge of one's own knowledge about effectiveness, usefulness, and limitations of cognitive strategies one considers for carrying out a cognitive task. Knowledge about the effectiveness of cognitive strategies can be procedural and/or conditional metacognitive knowledge.

**2. Metacognitive Regulation**

It refers to the regulation of cognitive processes to guide the selection and use of regulatory strategies and initiation of regulatory activities. Metacognitive regulation occurs before (planning), during (monitoring and control), and after (evaluation) a cognitive task. It is influenced by metacognitive knowledge and metacognitive experiences.

**2.1. Preregulation:** Refers to the process of regulating "the cognitive activity plan" in setting clear goals, selecting appropriate strategies, and deciding regulatory mechanisms to initiate and implement the cognitive activity (task). It regulates the cognitive system for effective planning with clear and appropriate goals, strategies, and regulatory mechanisms.

**2.2. Intraregulation**: Refers to the process of regulating "the execution of cognitive activity" by the deployment of appropriate regulatory processes and strategies. The regulatory processes, via monitoring and control, regulate the process and outcomes of cognitive activities by supporting the cognitive system in continuously assessing progress toward goals, evaluating the effectiveness of strategies, and making adjustments.

(a)*Metacognitive Monitoring*: Refers to the awareness and evaluation of task characteristics and one's cognitive processes during cognitive activity.

(b) *Metacognitive Control*: Refers to the online use of metacognitive monitoring information to support one's cognitive system in adjusting or modifying its activity.

**2.3. Post-regulation**: Refers to the process of regulating "the cognitive endeavor against the outcomes of its activity" through thoughtful evaluation. It regulates the cognitive system to make a thorough assessment of the effectiveness of strategies and the accuracy of results and reflects meaningfully for refining future cognitive activities.

**3. Metacognitive Experience**

Metacognitive experience refers to feelings and judgments one experiences regarding current, ongoing (online) cognitive activities.

**3.1. Metacognitive Feelings**: Refers to one's reflections, inferences, or intuitive responses that reflect one's fluency in performing cognitive activities.

(a) *Feelings of Familiarity*: One's feelings of familiarity with a certain cognitive activity.

(b) *Feelings of Knowing*: One's feelings of knowing something even though they cannot recall it at that moment.

(c) *Feelings of Difficulty*: One's feelings of difficulty in performing a certain cognitive activity.

(d) *Feelings of Confidence*: One's feelings of confidence in successfully executing a certain cognitive activity.

(e) *Feelings of Satisfaction*: One's feelings of satisfaction with one's cognitive activities and their outcomes.

**3.2. Metacognitive Judgments**: Refers to one's judgments about one's cognitive activities based on information and experiences.

(a) *Judgments of Learning*: One's judgment of learning a certain lesson or concept.

(b) *Judgments of Solution Correctness*: One's judgment of solution correctness for a certain problem-solving activity.

(c) *Judgments of Task Familiarity*: One's judgment of familiarity with a specific cognitive activity.

(d) *Judgments of Knowing*: One's judgment of knowing a specific learning content.

(e) *Judgments of Performance*: One's judgment of the quality of performance in a specific cognitive activity.