Metacognition in HCI: Designing Systems for Planning and Flexibility

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Abstract. Metacognition is essential for adaptability in complex environments but remains underexplored in Human-Computer Interaction (HCI). This paper leverages Sociotechnical GOMS (SGOMS) to model metacognitive processes like task switching, re-planning, and strategy adjustment. By introducing flexible "Planning Units" and integrating both reactive and deliberate metacognition, SGOMS addresses the limitations of traditional models. The proposed meta-HCI interface empowers users to simulate tasks and develop adaptive strategies, enhancing performance and resilience in dynamic settings.

Keywords: Metacognition • GOMS • SGOMS • Cognitive Modeling • AIS

1 Introduction

Metacognition, or "thinking about thinking," is increasingly recognized as a critical factor in enhancing expert performance and adaptability in complex, dynamic environments. While its relevance to fields like cognitive science and artificial intelligence is well established, its application within Human-Computer Interaction (HCI) remains underexplored, despite growing interest in the design of systems that support users' ability to monitor, evaluate, and adapt their interactions with technology [1, 2]. This is particularly crucial in high-stakes domains such as healthcare, transportation, and emergency response, where effective decision-making and error mitigation laregly depend on users' metacognitive engagement.

Traditional HCI frameworks, such as the Goals, Operators, Methods, and Selection Rules (GOMS) model, have demonstrated utility in modeling structured, routine workflows. However, these models often fail to account for the metacognitive processes required to navigate real-world scenarios characterized by dynamic re-planning and strategic adjustments [3]. Sociotechnical GOMS (SGOMS) addresses this gap by incorporating mechanisms for handling interruptions, task switching, and workflow adaptations, offering a more comprehensive framework for modeling human interaction in unpredictable environments [4]. While there have been efforts to integrate metacognition into HCI, these remain limited in scope and application. For instance, studies on human-in-the-loop systems reveal that metacognitive feedback can enhance situational awareness and improve users' ability to navigate complex tasks [2]. Further, emerging research highlights the potential of metacognitive scaffolding in educational contexts, such as intercultural design challenges, where reflection and adaptability play a central role in addressing cultural biases and fostering effective collaboration [6].

This paper presents a proposal for a cognitive model that can model expert tasks, including the metacognitive components. For this we will use SGOMS [3] and the Common Model of Cognition [6]. By employing such a model, metacognition can be included in simulations to test new interfaces, and incorporated into model-based Adaptive Instructional Systems (AIS).

2 Adaptive Instructional Systems

Adaptive Instructional Systems (AIS) are sophisticated platforms designed to customize instructional content, pacing, and feedback to align with individual learner needs and performance. Unlike traditional standardized methods, AIS dynamically analyze real-time interactions to boost engagement, retention, and knowledge acquisition [7]. By addressing variations in prior knowledge, cognitive capacity, and motivation, AIS contributes to greater educational equity and accessibility across diverse populations. These systems are highly versatile, adapting to a range of contexts, such as education, workforce training, and healthcare, by tailoring strategies to task complexity, available resources, and collaborative environments.

AIS operates through the interplay of three primary components: the learner, the environment, and agent-based tutors [8]. The learner model monitors cognitive states, prior knowledge, engagement levels, and emotional responses, allowing for personalized instruction through pacing adjustments, scaffolding, or content simplification. The environment component supplies contextual data, such as physical settings and resource availability, ensuring strategies remain appropriate and effective. Agent-based tutors function as intelligent guides, utilizing reinforcement learning to deliver feedback, adapt instructional approaches, and refine interventions based on learner performance. Together, these components create dynamic, continuously improving learning experiences.

A defining characteristic of AIS is their dual-layered adaptivity, which combines micro-adaptive and macro-adaptive mechanisms. Micro-adaptive mechanisms work in real time to provide immediate adjustments, such as offering hints or simplifying tasks, to address challenges and sustain engagement [7]. Macro-adaptive mechanisms, on the other hand, focus on broader instructional strategies, such as sequencing lessons and adjusting pacing, informed by periodic assessments to align with long-term goals. This layered approach enables AIS to address both short-term learning needs and overarching educational objectives, enhancing their applicability and effectiveness in varied settings.

3 Metacognition

Metacognition, often described as "thinking about thinking," refers to the processes by which individuals monitor, evaluate, and regulate their own cognitive activities [9]. It encompasses two primary components: metacognitive knowledge, which involves awareness and understanding of one's own cognitive processes, and metacognitive regulation, the strategies employed to guide and optimize cognitive performance [10]. These processes are foundational to effective learning, problem-solving, and decision-making, making metacognition a central topic in cognitive science and psychology.

Research in metacognition has highlighted its role in a variety of cognitive domains, demonstrating that individuals with higher metacognitive awareness outperform others in tasks requiring complex reasoning, memory, and attentional control [11, 12]. Moreover, metacognition is increasingly recognized as a skill that can be developed through training and practice, further underscoring its significance across educational and professional settings [13, 14].

Theoretical frameworks such as Nelson and Narens's [15] model provide a structured approach to understanding metacognition (see Fig. 1). This model differentiates between the meta-level, which monitors and controls cognitive processes, and the object-level, where these processes occur. The interaction between these levels allows for dynamic adjustments based on task demands, enabling individuals to navigate complex and dynamic environments more effectively.

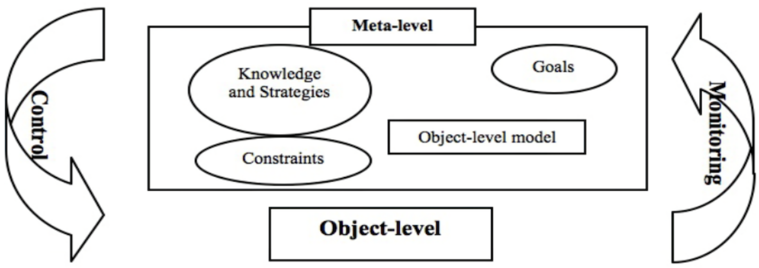

Fig. 1. Nelson and Naren's metacognitive model [16].

3.1 Metacognition in Expertise

The study of expertise has traditionally focused on automaticity, emphasizing the seamless execution of tasks through practice and experience. However, recent research highlights the pivotal role of metacognition in expert performance, challenging the view that expertise is solely characterized by "mindless automaticity" [17]. Instead, experts often engage in deliberate metacognitive processes to evaluate their actions, anticipate potential errors, and recalibrate their strategies.

In high-stakes domains such as aviation, medicine, and emergency response, metacognitive skills enable experts to adapt to unpredictable scenarios. For instance, a pilot faced with a sudden system failure must assess the situation, prioritize tasks, and make informed decisions under time constraints. Similarly, surgeons employ metacognitive strategies to anticipate complications and adjust their approach in real-time [16]. These examples illustrate how metacognition underpins the flexibility and adaptability that define expert performance.

Metacognition also plays a critical role in bridging declarative and procedural knowledge within expertise. While declarative knowledge provides a foundation of facts and principles, procedural knowledge involves the application of these principles in practice. Metacognitive processes facilitate the transition between these types of knowledge, enabling experts to refine their skills and adapt their strategies to novel challenges [10].

Metacognitive judgments in expert performance often rely on heuristic cues, such as fluency - the perceived ease of a cognitive process - which can create a strong Feeling of Rightness even when inaccurate [18]. The reliability of these judgments depends on the validity of the cues, which guide monitoring and regulation. Feedback that improves the calibration of confidence judgments can reduce overconfidence and enhance performance. This highlights the dynamic interplay between unconscious cues and deliberate thinking, where implicit signals help initiate and guide strategic adjustments in high-stakes tasks.

3.2 Dual System Metacognition

The dual-process framework of cognition, popularized by Kahneman [19], has been adopted by metacognition researchers as a valuable lens for understanding metacognitive processes [20, 21]. This framework distinguishes between System-1, characterized by fast, intuitive, and automatic processes, and System-2, which involves slow, deliberate, and analytical reasoning. Both systems contribute to metacognitive functioning in distinct ways.

System-1 Metacognition operates implicitly and procedurally, enabling rapid, automatic monitoring and correction of cognitive processes without the need for conscious deliberation. It relies on heuristic, non-conceptual mechanisms to evaluate the fluency or ease with which a psychological process unfolds. For instance, a software engineer might intuitively sense an error in a line of code, driven by pattern recognition honed through repeated experience. Similarly, a chess player might feel confident about a move without explicitly analyzing its merits, based on an implicit sense of board dynamics. This form of implicit metacognition is invaluable in time-sensitive or high-pressure situations, as it allows for quick, adaptive responses. However, its reliance on heuristics also makes it susceptible to biases and systematic errors, particularly when dealing with novel or complex scenarios.

System-2 Metacognition, by contrast, is conceptual and relies heavily on declarative knowledge. It involves explicit, reflective monitoring and regulation of cognitive processes, which allows individuals to flexibly plan and adjust to new or complex situations. This type of metacognition uses verbally expressible, conceptual representations to evaluate and guide thought. For example, a medical professional diagnosing a challenging case may engage in deliberate, step-by-step reasoning to identify potential causes, evaluate evidence, and determine the best course of treatment. System-2 metacognition excels in tasks that require precision, accuracy, and adaptation to unique scenarios, though it is cognitively demanding and slower than its System-1 counterpart. Its capacity for flexible adjustment and conceptual planning makes it particularly suited to address problems outside the scope of learned heuristics or routines.

The interplay between these systems is critical to skill acquisition and metacognitive development. Over time, System-2 processes - originally effortful and deliberative - can migrate to System-1, becoming more automatic, procedural, and efficient [22]. For instance, learning to drive a car begins with effortful attention toward explicit, rule-based reasoning processes (System-2), which gradually transforms into a largely intuitive and automatic process (System-1). This migration highlights the dynamic relationship between declarative and procedural metacognition, with System-2 laying the groundwork for more streamlined, System-1 operations.

3.3 Metacognition in HCI

The integration of metacognitive principles into Human-Computer Interaction (HCI) has gained increasing attention as technology becomes essential in high-stakes domains. Metacognition in HCI emphasizes the design of systems that support users' ability to monitor, evaluate, and adapt their interactions with technology. This is particularly critical in complex and dynamic environments, such as healthcare, transportation, and emergency response, where adaptability and error mitigation are paramount [1, 2].

Traditional HCI frameworks, like the Goals, Operators, Methods, and Selection Rules (GOMS) model, are effective for routine, well-defined tasks but often fail to incorporate the metacognitive processes necessary for real-world scenarios. These models lack mechanisms for dynamic re-planning, strategic adjustments, and adaptability, limiting their effectiveness in environments where users encounter unexpected challenges [4].

Recent advancements in HCI have addressed these limitations by integrating metacognitive frameworks. For example, the Sociotechnical GOMS (SGOMS) model incorporates metacognitive principles, enabling systems to manage workflow interruptions, task switching, and re-planning. SGOMS leverages metacognitive monitoring and control processes to support users in adapting to emergent demands, providing a more comprehensive approach to understanding human interaction with technology [3].

Further research highlights the importance of metacognition in improving decision-making accuracy and situation awareness in dynamic tasks. For instance, studies on human-in-the-loop simulations demonstrate that metacognitive feedback can significantly enhance users' situational awareness and ability to navigate complex systems effectively [2]. These findings underscore the need to design interfaces that not only facilitate task execution but also foster users' ability to monitor and regulate their cognitive strategies in real time.

Moreover, HCI education has begun to incorporate metacognitive strategies to address intercultural design challenges. For example, daily reflection sessions in intercultural contexts encourage users to develop metacognitive awareness, allowing them to adapt their design approaches and account for cultural biases [5]. Such educational interventions suggest that metacognitive scaffolding can significantly enhance both individual and collaborative performance in diverse environments.

Incorporating metacognitive principles into HCI thus offers a promising avenue for improving usability, adaptability, and decision-making in technology systems. These advancements pave the way for creating systems that not only meet immediate user needs but also foster deeper engagement and resilience in complex, real-world tasks.

4 SGOMS

The Goals, Operators, Methods, and Selection Rules (GOMS) model has long served as a cornerstone for cognitive modeling in HCI. Introduced by Card, Moran, and Newell in 1983 [23], GOMS is designed to analyze user performance in routine, well-defined tasks by breaking down activities into four hierarchical components: Goals (desired outcomes), Operators (basic actions such as keystrokes), Methods (sequences of operators used to achieve goals), and Selection Rules (criteria for choosing between methods). GOMS has proven effective in designing and evaluating user interfaces for tasks with predictable workflows. However, its reliance on linear task execution makes it unsuitable for complex, dynamic, or collaborative environments where interruptions and unexpected changes are common.

To address these limitations, West and Nagy [3] introduced the Sociotechnical GOMS (SGOMS) framework. SGOMS extends traditional GOMS by integrating macrocognitive principles, making it capable of modeling dynamic, real-world sociotechnical systems. The framework is specifically designed to handle interruptions, task switching, re-planning, and collaborative workflows (see Fig. 2).

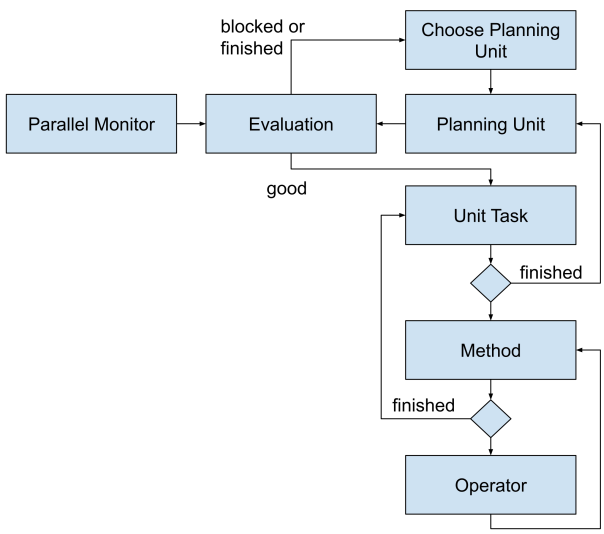

Fig. 2. SGOMS workflow.

4.1 Dynamic Task Execution and Adaptation

SGOMS models how users manage tasks that are subject to change due to environmental or situational factors. Unlike traditional GOMS, which assumes uninterrupted task execution, SGOMS incorporates mechanisms for dynamic re-planning and adaptation. This feature ensures that users can adjust their workflows in response to unforeseen events such as equipment failures or changes in task priorities.

Planning Units. A key innovation in SGOMS is the introduction of Planning Units, which organize tasks at a higher level than unit tasks. Planning Units represent goal-directed activities composed of multiple unit tasks, each with its own methods and operators. For example, preparing a presentation might involve unit tasks such as opening software, creating slides, and rehearsing. Planning Units are structured to allow for interruptions and resumption, enabling users to adapt seamlessly to changing conditions.

There are three types of Planning Units:
Ordered Planning Units. Tasks executed in a specific sequence.
Situated Planning Units. Tasks that can be executed in any order, and are triggered by external events.
Externalized Planning Units. Tasks guided by external systems or cues that manage initiation, execution, and completion.

Constraints and Shared Knowledge. SGOMS incorporates constraints such as deadlines, resource availability, and task priorities into its models to reflect real-world decision-making. These constraints guide the selection of Planning Units and help workers adapt their actions to current situational demands. Additionally, Planning Units serve as shared knowledge structures, facilitating collaboration and ensuring team alignment with broader organizational goals.

Parallel Monitoring and Evaluation. One of the most distinctive features of SGOMS is its parallel monitoring and evaluation mechanisms, which continuously assesses task progress and environmental conditions.

Parallel Monitoring. This involves observing both the external environment ("what's going on around me") and the internal state of the user ("how do I feel"). For example, if a tool is missing or a system error occurs, monitoring processes identify the issue and trigger further evaluation.

Evaluation. This ensures tasks are proceeding properly by monitoring interactions across operators, methods, and unit tasks. When discrepancies arise, evaluation mechanisms determine whether to continue the current Planning Unit or switch to another. This adaptability is critical in environments with frequent interruptions and unpredictable workflows.

By leveraging these mechanisms, SGOMS enables real-time adjustments to task execution, ensuring resilience and efficiency in dynamic contexts. For example, in emergency response scenarios, parallel monitoring might detect a resource shortage, while evaluation processes decide how to adjust the current workflow to address the issue.

Implications for HCI Design. SGOMS offers a comprehensive framework for designing interfaces that support adaptability and metacognitive engagement. By incorporating features like real-time feedback, task prioritization tools, and collaborative planning capabilities, SGOMS ensures that systems align with the realities of dynamic, interruption-prone environments. This makes it a valuable tool for enhancing user performance and resilience in high-stakes domains such as healthcare, aviation, and emergency response. Through its focus on Planning Units, parallel monitoring, and evaluation, SGOMS addresses the limitations of traditional GOMS, paving the way for more effective modeling of human behavior in complex sociotechnical systems.

4.2 SGOMS and The Common Model of Cognition

The SGOMS framework is part of the wider Common Model project. Rather than merely extending the traditional GOMS structures, SGOMS aims to serve as a model of human cognition within the Common Model paradigm. This marks a departure from the typical interpretation of GOMS within the HCI community, where it is predominantly regarded as a tool for hierarchical task analysis instead of a holistic cognitive theory.

The Common Model framework delineates cognition into three levels: neural, micro cognitive, and macro cognitive [3, 6]. Figure 3 provides a depiction of the micro cognitive structure. While the neural level investigates the physical implementation of the framework, this paper does not address that dimension. Conversely, the macro level explores the practical application of the framework to execute various tasks. This underscores the adaptability of the micro cognitive framework in managing tasks through diverse methodologies. SGOMS outlines a distinct strategy for leveraging the Common Model's microcognitive framework to simulate expertise. The model posits that, with ample practice and experience, individuals naturally gravitate toward this method when tackling real-world challenges.

4.3 The Common Model of Cognition

The Common Model of Cognition (CMC) is a modular cognitive architecture [24] designed to represent the mechanisms and processes that underlie human-like intelligence [6]. By incorporating elements such as working memory, long-term declarative and procedural memory, perception, and action, the CMC offers a comprehensive framework for analyzing cognitive mechanisms across a broad range of domains. As a consensus model, it synthesizes decades of research in fields like cognitive science, artificial intelligence, and neuroscience. Functional MRI studies have highlighted its effectiveness in mapping cognitive processes to specific brain regions and outperforming alternative models in explaining neural activity during tasks [25].

The architecture of the CMC is composed of distinct, interconnected modules, each reflecting a fundamental cognitive function (see Fig. 3). These modules include perception, responsible for processing sensory information; motor systems, which execute physical actions; declarative memory, storing factual and episodic knowledge; procedural memory, governing condition-action rules for automated behaviors; and working memory, which facilitates short-term processing and task coordination. These components operate within the cognitive cycle, a mechanism that handles deliberate actions approximately every 50 milliseconds. This cycle creates a serial bottleneck, allowing for the conscious selection of only one action per iteration, while parallel processing within individual modules supports multitasking and integrates multiple information streams [25].

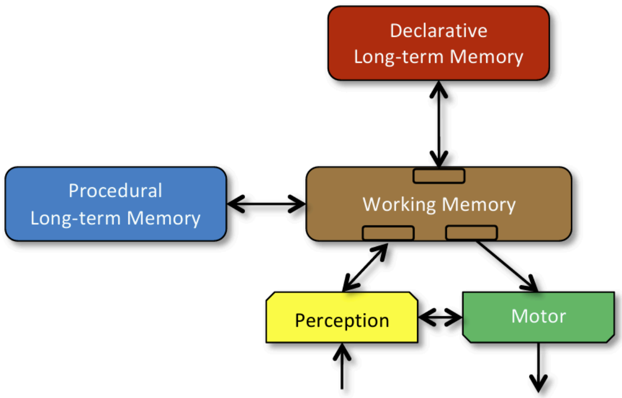

Fig. 3. The Common Model of Cognition [6].

The CMC processes information using both symbolic and subsymbolic representations. Declarative memory encodes explicit knowledge through relational structures and is enhanced by metadata such as frequency and recency to optimize retrieval and adaptive learning. Procedural memory employs condition-action rules to streamline routine tasks and guide decision-making. Working memory acts as a bridge between these systems, enabling the retrieval of knowledge, the coordination of motor actions, and the application of top-down influences on perception. This modular configuration, combined with its 50 ms cognitive cycle, allows complex behaviors to emerge through sequences of iterative cycles. Each cycle advances the cognitive state by focusing on a single deliberate act, balancing the trade-offs between limitations and adaptability. Within the Common Model, System-1 corresponds to procedurally-driven processes, while System-2 aligns with operations driven by declarative knowledge [22, 26].

This structure encapsulates the interplay between cognitive constraints and capabilities, offering a detailed and realistic depiction of human cognition. By facilitating the interaction of memory systems and modules, the CMC supports effective learning, decision-making, and task execution. Consequently, it provides a valuable framework for investigating cognition across various fields, especially in understanding aging and developing targeted interventions.

5 Modeling Metacognition in Expert Tasks

We argue that building SGOMS models of expert tasks in a cognitively realistic Common Model architecture, such as ACT-R, provides an accurate way of including metacognition in the model. This can then be used as a way of testing proposed interfaces through simulation and as a means to include AIS. Here we will examine how System-1 and System-2 metacognition manifest in each part of the model.

Creating and managing Planning Units within SGOMS can be viewed as a metacognitive process. Metacognition, or "thinking about thinking," involves the ability to reflect on, monitor, and regulate one's own cognitive processes. Planning Units serve as a structured way for users or agents to organize their actions in relation to overarching goals, requiring them to evaluate priorities, anticipate potential obstacles, and adjust strategies dynamically. When an agent decides how to structure a Planning Unit, they are engaging in a form of metacognition by determining the most efficient sequence of Unit Tasks and considering environmental constraints. This process not only involves task-level decision-making but also higher-level reasoning about how to achieve goals in the most effective way. Modifying or creating a new planning unit is an example of System-2 metacognition, requiring deliberate thought. However, the planning unit structure also supports fast System-1 metacognition, in that it prescribes where automatic interruptions can occur (i.e., between the unit tasks).

Parallel monitoring and evaluation are deeply tied to metacognition as they involve ongoing awareness and assessment of task performance and environmental factors. Parallel monitoring corresponds to the monitoring aspect of metacognition, i.e., being attuned to what is occuring in real time without necessarily intervening immediately. This process mirrors how individuals continuously track their own thoughts, progress, and the external environment during cognitive tasks, looking for specific task related triggers or signs that something unexpected has happened. This is largely a System-1 activity.

Parallel monitoring provides the raw signals that feed into the evaluation processes. Evaluation then determines whether the monitored information warrants an interruption to the planning unit. This involves looking at the interruption within the context of the planning unit being executed and the task-as-a-whole. Ideally, this should also be a fast, System-1 response. However, with unfamiliar interruptions it could involve System-2 deliberate thinking.

The evaluation function decides whether to signal an interruption to the planning unit, which triggers the *choose planning unit* function, and then uses constraint-based decision making to decide whether to switch planning units and which planning unit to switch to. This process would, in most cases, involve System-2 metacognition; deliberately thinking about the best way to continue given the nature of the interruption. It is also possible that a memorized or automatized rule could be applied here, which would be an instance of System-1 metacognition. As for unit tasks, methods, and operators, these do not qualify as metacognitive process during the task. However, in designing a new interface, they play a critical role in thinking about how to think about the task. Regular GOMS modeling is effective for designing interfaces for individual unit tasks or unit tasks done in a fixed order. However, in a task where agents need to strategically use unit tasks, SGOMS allows for a higher-level analysis. Specifically, designers need to consider the likelihood of interruption. In situations where interruptions are more likely, it is important to make the unit tasks shorter, so they may be completed if there is an interruption and not abandoned halfway.

Finally, another aspect of SGOMS metacognition is the use of planning units to coordinate multi agent activity. Planning units can be used to communicate and coordinate actions between agents. This level of planning involves considering the planning units that other agents are enaged in. For example, West and Nagy [3] found that server maintenance workers would consider the planning units that other teams were involved in when deciding which planning units they should complete next. From an interface design perspective, this aspect is often overlooked, however it is often important for workers to see what other workers are doing in order to make informed decisions. Here, it is essential to consider larger issues about work in general, such as privacy, cultural sensitivity, and even work-related decorum.

6 Conclusion

Expertise is not merely the ability to perform tasks automatically but also the capacity to adapt to novel challenges through deliberate reflection and strategic adjustment. SGOMS provides a framework for modeling this interplay, linking intuitive System-1 metacognitive processes with reflective System-2 metacognitive processes, meeting the real-world demands of experts in fields like aviation, cybersecurity, and disaster relief.

By emphasizing the value of metacognitive skill development, SGOMS highlights the potential of interfaces that encourage reflection, such as performance dashboards, to enhance both immediate performance and long-term adaptability. The development of "meta-HCI interfaces," informed by SGOMS and AIS, opens avenues for tools like interactive simulations and collaborative systems that improve decision-making and team coordination in dynamic environments.

The Common Model of Cognition further supports this vision by offering a realistic foundation for testing interfaces and instructional systems that prioritize metacognitive engagement. Together, these frameworks pave the way for adaptive, user-centered systems that foster expertise, resilience, and flexibility, equipping users to navigate increasingly complex technological challenges.

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