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Meta-Reasoning: Monitoring and Control of Thinking and Reasoning

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Abstract

Meta-Reasoning refers to the processes that monitor the progress of our reasoning and problem solving activities and regulate the time and effort devoted to them. Monitoring processes are usually experienced as feelings of certainty or uncertainty about how well a process has, or will, unfold. These feelings are based on heuristic cues, which are not necessarily reliable. Nevertheless, we rely on these feelings of (un)certainty to regulate our mental effort. Most metacognitive research has been focused on memorization and knowledge retrieval, with little attention to more complex processes, such as reasoning and problem solving. In that context, we have recently developed a Meta-Reasoning framework, used here to review existing findings, consider their consequences, and frame questions for future research.

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Trends Box

- Metacognitive research has largely focussed on the monitoring and regulation of memorization and knowledge retrieval. Recently, there has been a growing interest in the processes accompany performing more complex tasks, such as reasoning and problem solving.
- Meta-Reasoning processes have been studied with a variety of tasks that tap logical, creative, and mathematical skills.
- The findings converge with the Meta-Memory literature in some respects: subjective confidence is not always well calibrated with accuracy but nonetheless plays an important role in regulating effort.
- There are also points of divergence, due to the complexity of the processes being monitored and the length of time over which they unfold.
- The study of Meta-Reasoning sheds light on the processes that underlie reasoning and problem solving and has the potential to improve reasoning performance.

Glossary

Metacognitive Monitoring – Subjective assessment of how well a cognitive task is, will, or has been performed

Metacognitive Control –Initiating, terminating, or changing the allocation of effort to a cognitive task

Meta-Memory – Monitoring and control of learning and remembering

Meta-Reasoning – Monitoring and control of reasoning and problem solving

Initial Judgment of Solvability – The subjective probability that a problem is solvable, either by one's self or by anyone, based on a brief, initial, impression

Feeling of Rightness – Degree to which the first solution that comes to mind feels right

Intermediate Confidence – The subjective probability that each putative solution is correct

Final Confidence – The subjective probability that the final response to a problem is correct

Feeling of Error – The subjective experience that something went wrong and an error was made

Final Judgment of Solvability – After giving up on a problem, the estimated probability that the problem is nevertheless solvable

Metacognition and Meta-Reasoning

Metacognition refers to the processes that monitor our ongoing thought processes and control the allocation of mental resources. Understanding metacognitive processes requires one to think in terms of two levels [1]. Object-level processes carry out the basic cognitive work of perceiving, remembering, classifying, deciding, etc. Meta-level processes monitor those object level processes to assess their functioning (**metacognitive monitoring)** and to allocate resources as needed (**metacognitive control**- see Glossary). See Example-1 in Box 1. Monitoring processes operate in the background, in much the same way as a thermostat passively monitors the temperature of the air; they represent states of certainty or uncertainty about how well a set of processes has unfolded, or how likely they are to be successful. In the same way that the thermostat can send a signal to the furnace to start or terminate functioning, metacognitive processes are assumed to have a control function over the initiation or cessation of mental effort. In other words, if we are confident in our answer, we will act on it. If we are unsure, then we hesitate, gather more information, change tacks, etc. If we feel incapable of performing the task, then we may seek help or give up. The study of metacognition aims to understand the basis of these states of certainty as well as the role they play in allocating and regulating mental resources to a task.

Most of the extant research examines the metacognitive processes involved in learning, remembering, and comprehension, and has been motivated from an educational perspective. Much less is known about metacognitive processes in other domains, particularly with respect to complex processes such as reasoning and problem-solving. However, there has been a recent upswell in research in these domains (examples of tasks used to study meta-reasoning processes appear in Box 2). Our goal is to review what we currently understand about the monitoring and control of reasoning and problem solving. We have organized this review around the research questions listed in Box 3, which we see as the central questions guiding Meta-Reasoning research. Our goal was to provide the current state of the art in terms of answers to those questions, and to also identify gaps in the current scientific understanding of Meta-Reasoning processes (see Outstanding Questions Box).

Box 1. Real-life Examples

The Meta-Reasoning framework provides conceptual tools to assist researchers in understanding thinking and reasoning processes. Most research is carried out in the laboratory; however, the goal is, of course, to explain reasoning in real-life scenarios. The two examples below demonstrate the application of Meta-Reasoning concepts to everyday reasoning situations.

Example-1: *Object-Level vs. Meta-Level Monitoring and Control*

As you plan your first visit to Eiffel Tower in Paris, you study the Metro map. You see that you need to begin on one Metro line and then switch to another. Before leaving the hotel, you memorize the name of the station where you need to switch and plan a route from your hotel to the nearest station. Map reading, identifying Metro lines, and planning your route are **Object-level** processes. **Meta-level** processes monitor the object-level processes, for example, by letting you know how confident you are that you can find your way to the station. Meta-level control processes respond to these monitoring cues. For example, if you are not certain of finding your way, you may take your map with you. Similarly, as you ride the train, you may see that there are two stations with similar names. You may experience doubt that you correctly memorized the station in which you are going to switch trains, which might prompt you to ask another rider for directions.

Example-2: *Meta-Reasoning processes throughout the course of reasoning*

An experienced engineer is starting to design a bridge. Her experience with similar tasks supports high **Judgment of Solvability** that she can complete this task and thus she begins planning the design. She begins by consulting memory for potential building materials, common design options, ground conditions, prices, etc., aiming to find the combination that addresses the client's requirements. She comes up with her first potential design and considers whether it is adequate. She has medium-level **Feeling of Rightness,** which motivates her to come up with a better design. She thinks that this second design is better, but her current level of confidence (called **intermediate confidence** because it occurs during the task) is still not as high as she would like to have before deciding on the final design. After further thought, she realizes what bothered her: although this design is quite good, it is going to exceed the budget, which is not acceptable. At this point, she experiences a strong **Feeling of Error**, and calls a colleague to ask about alternative materials. She is then able to find different materials, which offer the right combination of strength and price. Now she is **confident** enough that her design addresses the client's requirements, and moves onto her next project.

In this preliminary version, Box 2 appears at the end of the file, as an appendix.

Box 3. Meta-Reasoning: Overarching Research Questions

We have organized this review around the following six questions, which are useful for categorizing the extant Meta-Reasoning research and for guiding future research:

1. Monitoring - Reasoning and problem-solving processes extend over a period of time: How are these processes monitored?
2. Control - What determines whether to continue, switch strategies, or terminate thinking about a problem?
3. What cues do we rely on to monitor our reasoning?
4. How does understanding Meta-Reasoning contribute to understanding the processes that mediate reasoning and problem solving?
5. How do individuals differ in their ability to assess their performance?
6. Can reasoning be improved by insights gained from Meta-Reasoning research?

The Outstanding Questions Box appears just before the references.

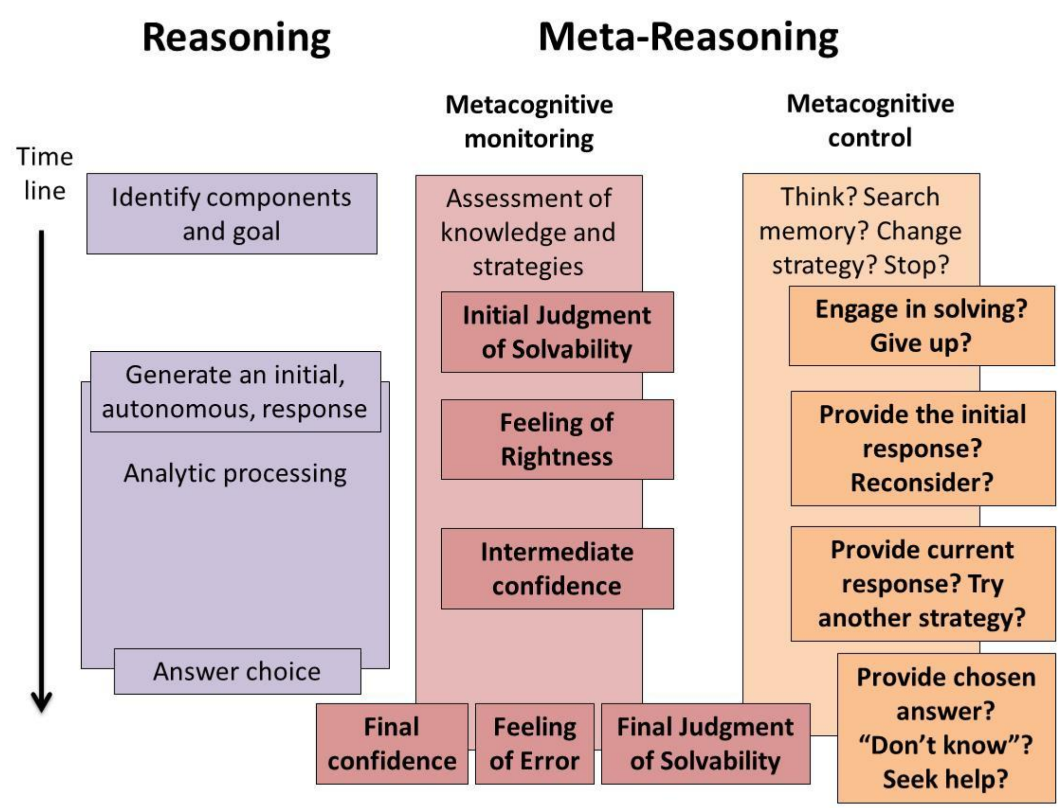

Figure 1. The approximate time course of reasoning and meta-reasoning processes.

Monitoring and Control in Reasoning and Problem Solving

The Meta-Reasoning framework that we propose is grounded in Nelson and Naren's seminal framework for monitoring learning and memory [1], which is still used today (see [2], for a review). Our framework is outlined in Figure 1 (see also [3, 4]). While it retains the basic architecture proposed by Nelson and Narens, it also reflects the complexity of the object-level processes unique to reasoning. The left column of boxes in Figure 1 represents the object-level processes involved in reasoning, with the understanding that various reasoning theories make different assumptions about the timing and nature of those processes.

The first pair of questions in Box 3 concern the processes involved in monitoring reasoning progress and their respective control functions. Figure 1, middle column, details the monitoring processes that we have thus far identified as relevant for reasoning, while the right column enumerates the associated control functions. All monitoring processes reflect a subjective assessment of the probability of success or failure on a given task, before, during, or after engaging in the task (see Box 1, Example-2). These assessments are mostly spontaneous [5, 6], and are hypothesized to trigger a variety of control decisions including taking action (see Box 1, Example-1), the allocation of time and effort to a task, and choice of strategy to complete the task (Box 1, Example-2).

Before embarking on a solving attempt, reasoners are posited to make an **initial Judgment of Solvability** [7, 8], which reflects the reasoner's assessment that the problem is solvable, and that it is solvable by her (Box 1, Example-2). This initial Judgment of Solvability is posited to control whether to attempt a solution, give up, seek external help, etc. There are cases in which reasoners can quickly and accurately identify whether the problem is solvable [9]. However, in many cases identifying unsolvable problems is not trivial [10], which can lead people to waste time trying to solve them [11].

Research on the Judgment of Solvability is still in its infancy. Consequently, we know only a little about the basis of this judgment (see next section), and less about how its strength might mediate subsequent processing. Understanding the basis of this judgment and its role in controlling subsequent processing is likely to be a fruitful direction for future research, given that humans tend to behave as cognitive misers, and are reluctant to invest effort in tasks they perceive to have a low probability of success [12].

So far, there are only two extant models that explain the relationship between monitoring and control of reasoning. The first is the Metacognitive Reasoning Theory [7]. This model deals with cases in which the context of the problem cues an immediate, initial answer to a problem (e.g., the Cognitive Reflection Test; see Box 2, D). This initial answer is proposed to have two dimensions: The answer itself, and a **Feeling of Rightness** that accompanies that answer (Figure 1)**.** The Feeling of Rightness has been studied using a two-response paradigm [13-15] in which reasoners give quick, intuitive answers to problems, rate their Feeling of Rightness, and then reconsider their answers[1] [13, 15, 16]. When the Feeling of Rightness is strong, it is a signal that further reconsideration is not required; consequently, reasoners spend little time rethinking their answer and are unlikely to change their minds [13-15]. In contrast, a weak Feeling of Rightness is accompanied by longer periods of reconsideration and a higher probability of changing answers. Importantly, because Feelings of Rightness are derived from cues that may be poorly correlated with accuracy (see next section), reasoners may be led to wrongly accept their initial intuitions with little reconsideration.

We note that the original framework for studying the Feeling of Rightness [7] was developed using the Dual Process Theory framework [17]. However, the logic of the Feeling of Rightness extends to single-process theories that do not propose two types of processing [18] and to theories that posit multiple parallel processes rather than sequential ones [16]. This flexibility is conveyed by the overlap between the boxes in the left-hand column of Figure 1. Given that understanding how and when people engage in effortful analysis is important, the issue of monitoring rapid, initial, answers is relevant regardless of the type of reasoning mechanisms that are proposed to underlie them.

[1] A number of steps have been taken to validate the two-response procedure. In order to verify that participants give their first, intuitive response, they are normally asked to verify that they did, indeed, respond with the first answer that comes to mind. To increase the odds that the first answer is given without reconsideration, the first response is often given under a deadline or cognitive load. There is also good evidence to indicate that giving the first response does not alter the nature of the final response.

The Diminishing Criterion Model addresses the relationship between thinking time, **Intermediate Confidence,** and **Final Confidence** [19] (Figure 1)**.** Because reasoning and problem solving take place over an extended period of time, participants' assessment of their performance and the possibility of success is constantly updated. Intermediate confidence is an internal gauge of the adequacy of potential solutions [11, 20, 21]. To study this process, reasoners are asked to give Intermediate Confidence ratings every few seconds until they decide on an answer, at which point they rate their Final Confidence. As with the Feeling of Rightness, the first such judgment in the series is a good predictor of the amount of time that reasoners spend on problems [19] and intermediate confidence tends to increase over time [13, 19, 20]. However, according to the Diminishing Criterion Model, as time passes, participants become more and more willing to give less confidently held answers: Early on, participants usually only provide answers when confidence is high; as time passes, they appear to compromise their standards and give answers in which they are less confident. Their degree of **Final Confidence** can be as low as 20% [19, 22], even when participants were given the option to opt out of answering, by responding "I don't know" [19]. Thus, people are willing to give low confidence solutions even when they could give up.

Recent work also suggests that, at least in some circumstances, people can identify when they have made a mistake. This is manifest both as differences in confidence ratings between correct responses and misleading ones [23, 24] and as a **Feeling of Error** [25-27]. Experiments using both the Cognitive Reflection Test and the Number Bisection Test (Box 2, D and H, respectively) showed that participant's Feelings of Error were higher after participants had made an incorrect, as opposed to a correct response. Because participants were not given the opportunity to correct or rethink their answers, it is not yet clear whether a Feeling of Error would exert a control function, i.e., by signaling the need for further reflection, as does a low Feeling of Rightness. It is also not clear whether a Feeling of Error is qualitatively different from a low Feeling of Rightness or whether they represent two ends of a single dimension of certainty.

Finally, a **Final Judgment of Solvability** [10, 11] is an assessment of solvability that is made after giving up on a problem. This judgment is posited to inform decisions about whether one should persist, perhaps by seeking help, or to desist, concluding that the problem is not solvable and does not warrant any further effort. For example, the engineer in Example-2 in Box 1 may come to the conclusion after working on the design for several days that she is not able to reconcile all of her clients' demands. She then has to decide whether someone else might be able to do so, or whether she should tell her clients that they need to remove some constraints.

In conclusion, we note that an important direction for future research is to investigate the control functions of the monitoring judgements described above. In addition, we note that there is a dearth of research on the variables that prompt a reasoner to give up. Indeed, in many experimental reasoning tasks, reasoners are not afforded the opportunity to "give up", even though this option is available in most real-world contexts.

Monitoring Reasoning is Cue-Based and Inferential

As we have argued above, Meta-Reasoning monitoring processes give rise to states of certainty and uncertainty. In this section, we address question no. 3 in Box 3 by describing factors that affect people's monitoring, i.e., the basis of their subjectively inferred probability of success. It is widely accepted that metacognitive judgments are based on heuristic cues, which are informed by beliefs and experiences associated with problem solving, and do not necessarily reflect actual performance. As such, the degree to which our monitoring processes are reliable is determined by the validity of the cues on which they are based [28].

For instance, a robust finding in meta-reasoning, as in many other domains [29], is that fluency*,* the perceived ease of responding, is a pervasive cue to certainty. For example, answers that come to mind quickly engender a strong Feeling of Rightness and Final Confidence, regardless of answer's accuracy [14, 22, 27]. Although much of the work on fluency effects is correlational, it is also possible to manipulate speed of processing to demonstrate a causal relationship, for example, by varying the delay between a problem and a putative solution [30]. Participants were asked to judge whether the presented solution to anagrams, mathematical equations, and Compound Remote Associates (see Box 2, B), was correct or not. Solutions that appeared shortly after the problems (50ms) were more frequently judged as being correct than those presented after a longer time (150ms or 300ms), regardless of whether they were correct or not. Thus, while the ease with which answers come to mind can be a proxy for problem difficulty, it may also be misleading. Consequently, judgments such as the Feeling of Rightness and Final Confidence may be poorly correlated with accuracy, because they are based on cues that are only partially correlated with accuracy [13, 22, 31]. Examining how these judgments dissociate from accuracy provides researchers a tool for discovering the heuristic cues that give rise to feelings of certainty (see also [10]).

It is not always the case that the cues are misleading. For example, problems that give rise to two conflicting answers (e.g., Cognitive Reflection Test, Box 2, D) are reliably more difficult (in terms of both response times and errors) than those that cue a single response; they also elicit lower Feelings of Rightness and Final Confidence than their single-answer counterparts [13, 15, 24]. In contrast, however, pronounceable anagrams (e.g., HIWEN, Box 2, E) are harder to solve than unpronounceable ones (e.g., HNWEI), but people judge them to be easier [8]. Familiarity is also a misleading cue: using familiar content in logical reasoning problems (see Box 2, I) can reduce performance, because it means that people may be biased by their background knowledge [32]. People are nonetheless more confident when reasoning about familiar than unfamiliar material [31, 32], even when the familiarity is experimentally induced by priming [21].

We note that it is widely assumed that reliance on heuristic cues is *implicit*, in that reasoners may sense a state of certainty or uncertainty, but not understand the origins of this feeling (experience-based cue utilization [28]; see [33], for review). Despite the broad acceptance of this assumption [2], recent discussions highlight interactions between implicit and explicit monitoring processes. These discussions are important both theoretically and practically. For example, a potentially important step to improving reasoning (see last section below) is to understand how people's beliefs about the bases of their confidence affect their monitoring [34], as well as the degree to which those beliefs can be experimentally manipulated (e.g., [35, 36]).

Understanding Meta-level Processes may elucidate Object-level Processes

As we have argued above, understanding the processes that give rise to confidence (or undermine it) are important in their own right, given the role that certainty plays in initiating action. Here, we argue that the Meta-Reasoning framework that we have proposed has also an important role to play in elucidating the nature of object-level reasoning processes (Box 3, Question no. 4). For example, one of the most surprising findings that has come to light using the two-response framework outlined above is that reasoners often do not change their answers during a period of reconsideration, which means that when the answer is correct, it was correct from the start [15, 37]. This finding has profound implications for theories of reasoning that rely on deliberate, analytic thinking to correct erroneous intuitions [17, 38, 39]. Contemporary methodologies, like eye-tracking and mouse-tracking may further elucidate how reasoning processes change over time [40, 41].

Equally, the absence of deliberate thinking plays an important role in the explanation of many so-called reasoning biases. For example, the Cognitive Reflection Test (Box 2, D) is a case where most people have the ability to find the correct answer, but fail to do so nonetheless. That is, they fail to take the time to reconsider their initial response. In our view, this is essentially a metacognitive phenomenon which could stem from several sources: A) the reasoner has a strong Feeling of Rightness, which signals that further reconsideration is not necessary, and moved on [13, 42]. B) the Feeling of Rightness is weak, but nonetheless sufficient to meet the reasoners' current aspirational level [19], C) the reasoner may not prioritize getting the answer correct, possibly because of time constraints, or because getting it right might require them to invest more time or effort than they are willing to [19, 43].

As mentioned above, final confidence is generally higher than confidence in initial responses. Keeping track of the intermediate confidence ratings as they accumulate during the solving process allows researchers to differentiate between answers that are provided after insight, which manifests as a sudden spike in confidence, as opposed to the more gradual accumulation of confidence that accompanies non-insight solutions [19, 20].

In addition to understanding why people terminate processing prematurely, a metacognitive analysis may help to understand cases where processing continues for too long. Many of the strategies posited to underlie reasoning processes are fast and frugal, in that people make decisions with relatively little information [44]. However, the evidence shows that reasoners frequently continue to gather more information than needed [45], even when they have to pay for the information and even when it is objectively useless (see [46, 47], for reviews). The question is: Why? One explanation might be that reasoners set an aspirational level of confidence and continue to gather information until they reach that level [19]. Similar findings have been reported in other domains, such as perceptual decision making, where people have been shown to continue to accrue evidence that will inform confidence after they have made their decision [48]. Note that this hypothesis assumes that the information need not be useful, simply that more information engenders confidence.

Individual Differences in Meta-Reasoning Ability

We know that individuals' performance on one cognitive task correlates with how they do on other tasks. This association may be due to the contribution of general cognitive ability [39]. Recently, in answer to Question no. 5 in Box 3, evidence has emerged showing that there is a similar positive manifold in both confidence and overconfidence people have in their performance across reasoning tasks [49, 50]. In contrast, measures of resolution (i.e., the ability to discriminate right from wrong answers) show less consistency across measures [51], although reasoners who show good resolution tend to show better performance [50].

Importantly, confidence has been found to predict decision-making style [50, 52]. To test this hypothesis, reasoners were asked whether they wanted to take action on each decision, for example, by submitting an answer for marking or administering a treatment for a fictitious disease [52]. It was found that confident reasoners take actions that are congruent with the decision they made, regardless of whether it was accurate. A strong association between confidence and action suggests a high degree of control sensitivity [53]. Consequently, those who are overconfident make errors of commission (act when they should not), whereas those who are underconfident make errors of omission (fail to act when they are correct). Notably, though, these studies also found that decision-making style tended to be context specific, as opposed to a stable individual trait, leaving open the question of how to assess decision-style in a particular context.

A related phenomenon is that miscalibration tends to be systematic: Those who do poorly at a task tend to overestimate their performance, while those who do well tend to underestimate it [54]. This finding has been recently generalized to reasoning tasks, such as those described in Box 2 [55]. People who scored poorly on a standardized battery of critical thinking problems [56] were also more likely to overestimate their performance on the Cognitive Reflection Test, and to over-estimate their disposition for analytic thinking on self-report measures.

Gender and culture are two important individual differences yet to be investigated as potential mediators of Meta-Reasoning processes. We know, for example, that men are relatively more confident than women when solving mathematics problems, even when there is no difference in performance [57]. We also know that decision-making styles vary across cultures [58, 59]. Even within a given culture, decision making styles differ between those who are politically liberal vs. conservative [58] and those who are more or less religious [60-62]. An open question is the extent to which gender and cultural variability in reasoning are associated with variability in meta-reasoning processes (e.g., [63]).

Improving Reasoning by Improving Meta-Reasoning

Given that people's monitoring judgments (and the subsequent allocation of time and effort) are mediated by cues that are not always well calibrated with accuracy. Clearly, having well-calibrated monitoring processes that reliably inform us when we need to rethink a situation is a critical aspect of successful reasoning (Box 3, Question no. 6). Data from educational contexts suggest that feedback about the accuracy of learners' confidence may both increase test performance and reduce overconfidence [64-66].

Some modest success in improving reasoning monitoring has been achieved with undergraduates. Training university students how to solve syllogisms (Box 2, F) that were particularly challenging reduced overconfidence, but did not improve their ability to discriminate right and wrong answers [67]. Overconfidence was also reduced when participants who worked in a computerized environment were allowed to solve logic problems under free time, rather than under time pressure [68]. Framing the task as the primary task, rather than a training phase, also reduced overconfidence. Thus, there is preliminary evidence that monitoring accuracy can be improved, but clearly, there is much more work needed to determine which interventions are likely to be effective and in what circumstances.

Concluding Remarks and Future Perspectives

We have argued that the processes that monitor our cognitions are low-level, implicit, and cue-based, even in activities, such as reasoning and problem-solving, that rely extensively on explicit, deliberate thought. This observation leads to an apparent paradox in that deliberate, analytic thinking may be initiated and terminated in response to unconscious, implicit cues. As such, we argue that understanding the processes involved in Meta-Reasoning is crucial to understanding reasoning proper, particularly in terms of understanding why thinking about a reasoning challenge is terminated prematurely or unnecessarily extended.

Outstanding Questions

- ❖ What control functions do early Meta-Reasoning judgments have over the initiation and termination of analytic thinking?
- ❖ How do later judgments affect subsequent behavior, such as giving up a reasoning challenge, seeking help, consulting others?
- ❖ What variables underlie a decision to “give up” on a problem?
- ❖ What are the cues on which these judgments are based?
- ❖ Do reasoners have insight into the sources of certainty in their judgments?
- ❖ How are Meta-Reasoning processes shaped by culture?
- ❖ Can we improve reasoning performance by improving Meta-Reasoning processes?

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Box 2. Examples of tasks used to study Meta-Reasoning:

A. Remote Associates Test (RAT) [21]

Description: Three words are presented. The task is to find a fourth word, which is related to each of the three words.

Example: Dew, Comb, Bee →Honey

B. Compound Remote Associates (CRA) [10, 19, 22, 30, 49, 68]

Description: Similar to the RAT, except that the goal is to find a fourth word that generates a compound word or a phrase (rather than a free association) with each of the three words.

Examples: Rocking, Wheel, High →Chair

Dew, Comb, Bee → Honey

C. Water-jar problems [11]

Description: Water amount are spread among several jars. Water must be transferred among the given jars to obtain a goal quantity in one jar.

Example: Jar A has a capacity of 3 liters and is empty at the start.

Jar B has a capacity of 5 liters and has 2 liters to start.

Jar C has a capacity of 9 liters, and starts full.

The goal is to have 0, 3, and 8 liters in A, B, and C jars, respectively.

(The correct solution is: B→A, C→A, A→B)

D. Cognitive Reflection Test (CRT) [12, 14, 19, 22, 24, 69]

Description: A set of three math problems, having simple computational requirements, but all require overcoming an initial, misleading response.

Example: A bat and a ball cost $1.10 in total. The bat costs $1.00 more than the ball. How much does the ball cost? _____ cents → 5 cents (10 cents is the misleading wrong answer, given by a majority of participants)

E. Anagrams [30]

Description: Scrambled words to be unscrambled to form a real word; participants may also be asked to judge whether it is possible to do so.

Example: IPSDEOE → Episode

F. Conditionals and syllogistic reasoning [23, 32]

Description: Participants get two premises and one or more conclusions; they are asked to assume that the premises are true and decide whether the conclusion(s) necessarily follows:

Example: If someone glebs, then they are brandup

A person is brandup

One can conclude that:

1. The person glebs
2. The person does not gleb
3. One cannot conclude if the person glebs or not (correct answer)

G. Raven's Matrices [50, 70]

Description: Participants get a 3X3 matrix of graphic symbols. Rows and/or columns are ordered by one or more rules. The bottom right-hand symbol is missing. Participants are to choose, in a multiple-choice test format, the option that logically completes the matrix. The source for this task is Raven who developed a test measuring abstract reasoning and regarded as a non-verbal estimate of fluid intelligence [71].

Example: See illustration in Figure 2 (correct answer is 6)

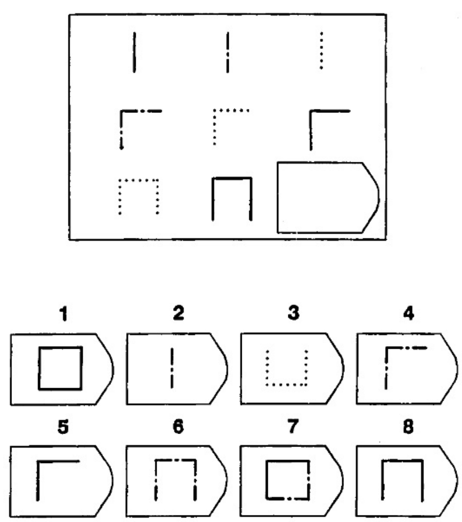

Figure 2. Example of a Raven's Matrix [71].

H. Number Bisection Task [25]

Description: In the Number Bisection Task, participants determine whether the number presented in the middle of a triplet corresponds to the arithmetic mean of the two outer numbers with a Yes/No answer.

Example: 12 – 21 – 30 (correct answer: Yes)

I. Logic problems [20, 68, 72]

Description: This is a diverse category. It includes verbal and spatial problems that can be solved by the application of logical rules.

Example: Joe and Dan are old friends who have not met for many years. As they catch up, Joe asks Dan how many kids he has. “Three,” answers Dan. “And how old are they?” says Joe. “Well,” says Dan, “the product of their ages is 36.” “Hmm,” says Joe, “can you give me a little more information?” “Okay,” says Dan. “The sum of their ages is exactly the number of beers we had today.” “That helps,” says Joe, “but it’s not quite enough.” “Okay,” says Dan. “So I’ll add that the elder one has a green bike.” Joe now knows how old the kids are. How?

Correct answer: 2, 2, 9