# A step toward decision-making assistance: Understanding pilots' decision making and workload impact

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**Abstract.** Aviation is a dynamic, time-pressured domain, where pilots are required to make quick and accurate decisions using multi-source information and in line with potentially multiple and changing goals. Despite pilots' high-level training and optimized cockpit automation, however, decision-making errors are observed. We conducted a review of multiple decision-making models and highlighted the influence of cognitive control modes on the quality of the decision-making process. The different frameworks of cognitive control incorporate external factors, such as time pressure or the number of goals, and individual factors, such as expertise, experience, and skills. These elements seem to be congruent with some mental workload models emphasizing regulation mechanisms, which are also based on cognitive trade-off. Accordingly, we can expect an impact of the workload level on the selected control mode involved in decision making. The instantiated cognitive control mode is assessed through the evaluation of the situation requirements and the physiological measurements of the use of attentional resources.

**Keywords:** Naturalistic decision making, Cognitive control, Mental workload, Cockpit, Aviation

## 1 Introduction

To understand human activities in complex dynamic situations, several features need to be considered, such as the uncertain and time-pressured nature of the environment, ill-structured problems, the amount and diversity of information, multiple and potentially changing goals, workflow interruptions, multiple actors, high stakes, and organizational rules [1][2]. Aviation can be viewed as a complex dynamic situation where some of these characteristics can be found. As a consequence, and despite high-level pilot training and a highly optimized cockpit design, decision-making errors are still observed [3] [4].

Accordingly, greater understanding of the degradation of pilots' decision making remains a significant challenge. After a review of decision-making models, highlighting the influence of cognitive control on the decision-making quality, we consider the link between mental workload and cognitive control. This perspective will enable us to investigate the nature of pilots' decision-making *via* the measurement of the mental workload level.

# 2 Theoretical framework: Exploring the relationships between the decision-making process, cognitive control mode, and mental workload

## 2.1 Decision making

As our goal in this segment of the study was to understand the decision-making process, we examined relevant research that has been conducted over the last decades, including the main two decision-making research streams, namely analytical models for decision making and the Naturalistic Decision Making (NDM [1]) framework. While analytical models for decision making were investigated in controlled environments, NDM models describe the decision-making process as it takes place in natural environments, where experienced people actually work. These two approaches complement each other for greater understanding of the whole decision-making process.

Examining these models led us to combine significant features of each model with the integrative Dynamic Situation Management (DSM [5]) model. The latter describes the way operators take decisions based on a mental image of the situation, called "occurring representation". DSM is based on the double-ladder structure [6] with a situation diagnosis phase on the left side, an identification and evaluation phase at the top, and an action-planning phase on the right. In the double-ladder model, if operators act on the system, they must perform a new detection and identification phase to take into account the effects of their action. In the DSM model, the effects of the action are immediately perceived and taken into account in the operators' representation, which reflects human behavior more accurately.

The double-ladder structure introduces the Skill-Rule-Knowledge (SRK) performance levels [7] into DSM. Automated processing, which goes directly from detection to action execution, is represented at the bottom of the model. It is the equivalent of the "skills" performance mode in the SRK model. The medium level, which goes from identification to action planning, is the equivalent of the "rules" performance mode. At this level, operators recognize a situation for which they have a set of rules and apply these rules. The upper level is the equivalent of the "knowledge" performance mode, where operators, using their knowledge, elaborate a representation of an unfamiliar situation for which no know-how or rules are available [7]. Fig. 1 shows how the integrative DSM model integrates different factors.

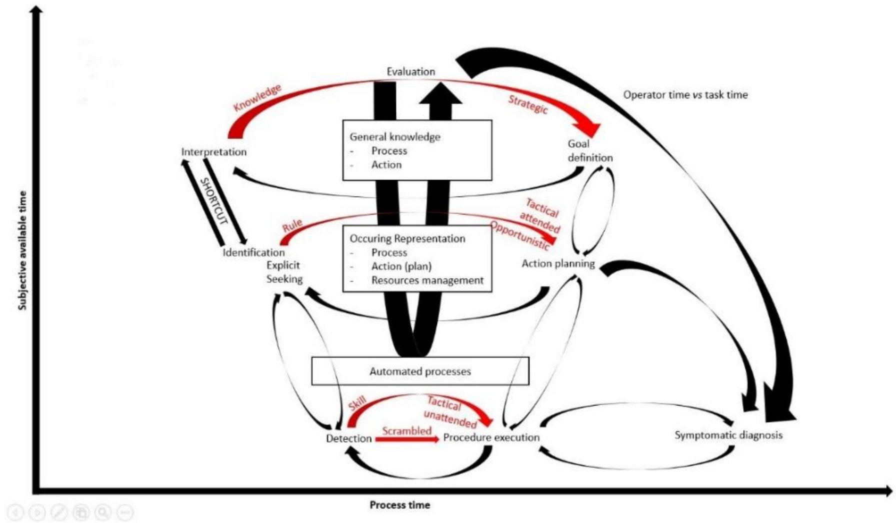


**Fig. 1.** The integrative Dynamic Situation Management model (based on Hoc and Amalberti 1994)

The DSM model can also include the Data-Frame model of Sensemaking [8], which explains how people proceed to understand a situation. Sensemaking involves connecting external data with a frame that is in the operators' mind. A frame is "an explanatory structure that defines entities by describing their relationship to other entities" (p. 118) [8]. External data (entities) are first detected and perceived at the bottom left of the DSM model. Then, operators try to understand these data using their knowledge: they try to connect the perceived data with an explanatory frame. This process takes place in the representation they construct. The situation is identified when there is congruence between the frame and the data (Fig. 2). Once found, the right frame can even provide some additional data from the operators' knowledge base.

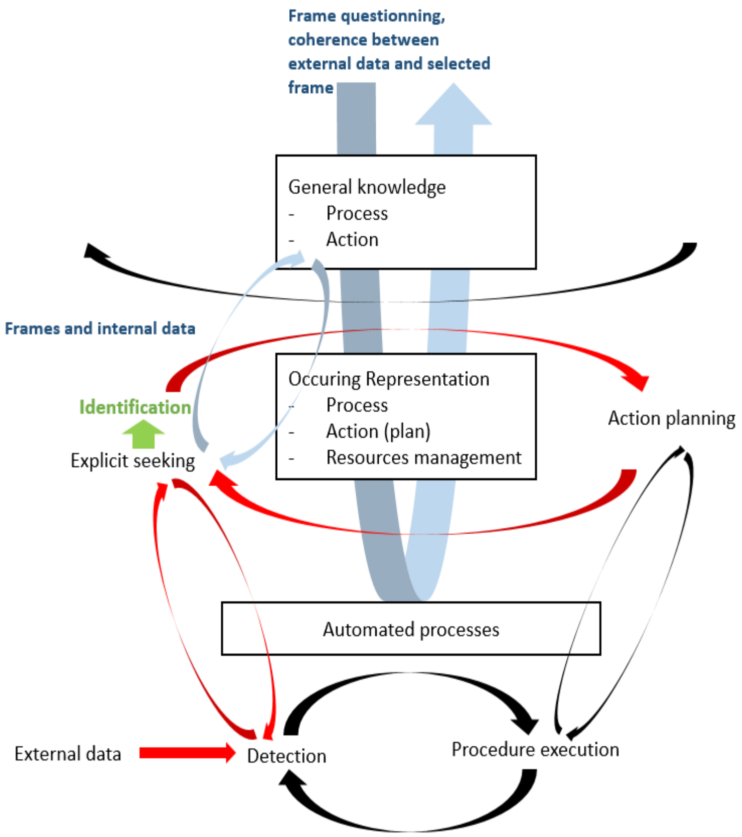


**Fig. 2.** Partial view of the Dynamic Situation Management model showing the integration of Sensemaking.

This review of decision-making models highlights the issue of how the various models characteristics are used to implement a decision process that is suitable for each situation. Hence, we focused next on cognitive control models, as these use the same features.

## 2.2 Cognitive control modes

### 2.2.1 Theoretical models

Cognitive control refers to processes that enable information processing and behaviors to vary adaptively from moment to moment, depending on current goals, instead of remaining rigid and inflexible [9]. There are multiple models that describe operators' cognitive control. They do not all take the same factors into consideration, and they do not all describe the same processes; hence, there is not "one" sufficient model. Consequently, it was necessary to combine several models in order to take more factors into account.

Hollnagel's Contextual Control Model (COCOM) [10] focuses on the complexity of the situation, regardless of the operators' competence. Four control modes are presented: scrambled, opportunistic, tactical attended and unattended, and strategic. Their use is determined by the complexity of the situation, which is function of the subjective available time, the number of tasks, and the match between expected and actual events. Hence, when there is an unlimited amount of time, operators are able to plan their actions on the long term and to take into account multiple goals: this is the strategic mode. At the other end of the spectrum, if there is no sufficient available time to understand the situation, operators will implement random, non-planned and non-considered actions: this is the scrambled mode. All four modes are detailed in a later section of this article.

The metacognitive control model presented by Hoc and Amalberti [11] shows a synthesis between two models. It takes into account the operators' internal data presented in the SRK model and the environmental data on which the COCOM is built. It also takes into account the symbolic/subsymbolic nature of data. When operators perceive data at a symbolic level, they understand its significance for the system they are dealing with. If the data are perceived at a subsymbolic level, operators just treat the data as they are, with no added significance [2]. Depending on operator expertise and the complexity of the situation, four control modes are available. Metacognitive control is present, ensuring the constant selection of the correct control mode depending upon the situation. Going beyond a mere synthesis, this model adds a significant feature by describing the fact that an expert facing a new situation will act like a novice, and that a novice encountering an already known situation will act more like an expert [9].

In sum, the instantiation of a cognitive control mode is the result of multiple external and internal factors. The amount of subjective available time is taken into account in addition to the number of tasks or the familiarity of the situation.

### 2.2.2 Synthesis

A synthesis of the various features of these models is necessary for greater efficiency and ease of use. In Table 1, we associated some aspects of the COCOM with the SRK levels and the origin and type of data from Hoc and Amalberti's model [11].

**Table 1.** Links between the COCOM cognitive control modes, the SRK levels, and the origin and type of data.

| *(COCOM)* Mode | *(COCOM)* Available subjective time | *(COCOM)* Familiarity of the situation | *(COCOM)* Type of actions | *(SRK)* level | *(Metacognitive control)* Origin and type of data |
|---|---|---|---|---|---|
| Strategic | Abundant | Known or not | Prediction-based | K | Internal data (if situation known) or external (if new), and symbolic |
| Tactical attended | Sufficient but limited | Known but important task load | Plan-based | R | Internal data, and symbolic |
| Tactical unattended | More than sufficient | Known | Plan-based but unreflective | S | Internal data, and subsymbolic |
| Opportunistic | Not sufficient | Vaguely recognized | Association-based | R | External data, and subsymbolic |
| Scrambled | Very insufficient | Not recognized | Random | | External data, and subsymbolic |

In the left column, the four control modes (scrambled, opportunistic, tactical attended and unattended, and strategic) are presented. The tactical mode is divided into two modes (attended and unattended) as proposed by Hollnagel [10].

First, the link between the cognitive control modes and SRK levels is easy to establish. When there is an abundant amount of time available, operators can use the strategic mode. This mode is used to plan an elaborate course of actions, using the operators' general knowledge to understand an unknown situation. Hollnagel describes this mode as providing "a more efficient and robust performance than the other modes" (p. 15) [10]. Thus, it is reasonable to assume that in this mode, operators will use the K performance level. We can, however, hypothesize that the strategic mode can be instantiated even in a known situation, when operators want to enhance their habitual course of actions to obtain a more optimal result, if there is an abundant available subjective time.

The tactical attended mode is not as reflective as the strategic mode, but still requires a non-negligible amount of attention. The tactical attended mode is instantiated in quite familiar situations. It is used when there is less available time than in the strategic mode. It is "the meticulous and careful execution of procedures and plans" (p. 14) [10]. In this mode, the operator will use the R performance mode.

The tactical unattended mode is instantiated when operators encounter a routine situation for which they know exactly what to do. The S performance mode is used, even if there is a great amount of time.

The opportunistic mode is instantiated when the context is not clearly understood, and the operator's knowledge is inadequate [10]. There is less available time than in the tactical mode, and the operator does no planning or anticipating. In this mode, the R performance mode is used.

Finally, in the scrambled mode, operators do not recognize the situation they are facing; this would require the use of general knowledge to go through the Sensemaking process. However, there is not enough available subjective time to do that. Operators implement random actions, and this mode matches with none of the defined performance levels. The operator is in a "blind trial-and-error type of performance", and there is almost "no reflection or cognition involved" (p. 14) [10].

We can also make a link between the SRK levels and the origin and type of data explained in the metacognitive control model. The K performance level is used for both known and unknown situations. In known situations, mostly internal data (data in the operators' mind) will be used, whereas external data (available in the environment) will be used in unknown situations. These data will be perceived at the symbolic level. At the other end, in scrambled mode, external data will be used since operators do not recognize the situation, and the data will be perceived at the subsymbolic level. In the case of the tactical unattended mode, even if the situation is known and the available time sufficient to cope with the situation, data will be perceived at the subsymbolic level. This feature shows the cognitive economy principle; even if there is enough time to elaborate a plan, as in the strategic mode, the situation is so familiar to operators that the required actions are known and executed without further consideration [10].

After detailing the decision-making process and the cognitive control modes, it is worth exploring the existing links between them.

### 2.3 Relationships between cognitive control and decision making

We have shown that the cognitive control mode depends on multiple factors, either internal to operators (e.g. expertise, experience, skills) or external, relative to the situation (e.g. available time, data, number of tasks). These factors are important to the integrity of the decision-making process.

Operators need to understand the situation they are facing, given their knowledge, the environmental data, and the available time. If there is a considerable amount of data to take into account, operators will need more time to process the data. This amount of time increases if the situation is new to operators, since the Sensemaking process then takes more time to complete due to the absence, in the operators' mind, of the frame that needs to be constructed [8]. Hence, if the available time is shorter than the time operators need to understand the situation, their occurring representation is incomplete or incorrect. As the planning of a course of action relies on a reliable occurring representation, the actions operators implement may not be adapted to the situation.

In this respect, an efficient control mode implies correct decision making, reducing the risk of errors. This is the case, for example, of the strategic mode, where there is abundant available subjective time, enabling operators to understand a situation correctly and plan a course of actions. On the contrary, a less efficient cognitive control mode can induce the degradation of the decision-making process. This is the case of the scrambled mode, where operators do not have enough time to understand the situation and implement random actions [10].

These arguments highlight the fact that the quality of the decision-making process depends, through cognitive control, upon the demands of the situation (available time, number of tasks, number and type of data) and on the processing capacity of operators. In his 1977 study, Sperandio [12] defined these two elements as responsible for the modulation of the variable called *workload*. This notion is examined in the following section.

### 2.4 Workload

The workload depends upon the combination of external (relative to the situation) and internal (relative to the operator) factors. The task demands indicate the difficulty of the task, the number of tasks, and the available time. The internal factors are the operators' characteristics that make the task more or less complex for them. The workload thus induces a limit to the operators' processing capacity and the acceptable load for them [12].

Operators adjust their strategies in line with these parameters. If the task demands are quite low, given the elements to take into account, the task difficulty, and the available time, operators can make optimal decisions. If the task demands increase, either through task difficulty, number of tasks, or reduced available time, operators adapt their strategy to avoid the overload phenomenon, namely the moment when the task demands exceed their acceptable load, given their processing capacity [12]. Operators prioritize tasks, consider fewer secondary objectives, and implement actions that just work, even if they are not optimal. This strategy illustrates the cognitive economy principle whereby operators adapt their strategy in order to avoid overload and keep some resources available to process other tasks that may eventually arise [12].

We hypothesized that these adaptation strategies demonstrate the instantiated cognitive control mode. In view of the task demands and the operators' state, a more or less efficient mode is used in order to keep an acceptable performance level while saving resources for unexpected events. If the task demands exceed the operators' capacities, the cognitive control mode instantiates a less adapted and efficient mode than necessary. This outcome involves a course of action that is not based on a correct representation of the situation, either not understood or with missing data, or random actions in the case of the scrambled mode.

It is then possible to establish a relationship between the instantiated cognitive control mode and the workload level, which can be shown by the *mental* workload level [12] [13].

### 2.4.1 Mental workload

A state of the art study conducted by Young, Karel, Brookhuis, Wickens and Hancock [13] considers the mental workload concept as a multidimensional construct. Like the workload, it is determined by the characteristics of the task (e.g. demands, performance), the operators (e.g. skill, attention), and the environmental context in which the performance occurs.

This study assumes that the mental workload is suboptimal if the operators' performance is below a required, desired, or imposed minimum level. A suboptimal mental workload is the result of overload or underload [14]. Overload occurs when operators are faced with more stimuli than they can handle while maintaining their own standards of performance. This effective load can affect selective attention, among other consequences. Conversely, underload is the result of too little stimulation and allocation of resources elsewhere [15]. Hence, it is possible to assume that both overload and underload can lead to performance degradation, attentional lapses, and errors [16], and that there is an optimum range of mental workload that is associated with best performance.

The mental workload can be examined through an attentional perspective; it entails a balance between the automatic and controlled processing involved in a task. Automatic processing is associated with expert performance; it is fast, unconscious, and does not use attentional resources. Controlled processing is the opposite [17]. This approach assumes that automatic processing releases attentional resources for other tasks, which decreases the mental workload level. These two kinds of cognitive processing are in line with the SRK performance levels that are involved in cognitive control and decision-making processes, where the skill level entails automated processing, and rules and knowledge levels entail more controlled processing.

Many mental workload models have been developed. For instance, one study by Kostenko, Rauffet, Chauvin and Coppin [18] synthesizes different mental workload approaches to create a dynamic multi-dimensional model. This model posits that operators select a strategy according to their perception of three criteria: their behavior, their performance and the situational constraints. The pairwise comparison of these criteria reveals regulation loops that enable operators to select a strategy and regulate their activity.

Another model focuses upon a few regulation loops. Cegarra [19] has developed a mental workload model (Fig. 3) that takes into account multiple factors such as the requirements of the situation, the self-assessed performance, the operators' strategies and perception of the system that are known to have an effect on mental workload modulation, and operators' *mental workload experience*. In addition to these factors, Cegarra examines the regulation loops that help operators maintain their mental workload level in the optimum range associated with the best performance, adapting their strategies in line with their perception of the system and their mental workload experience.

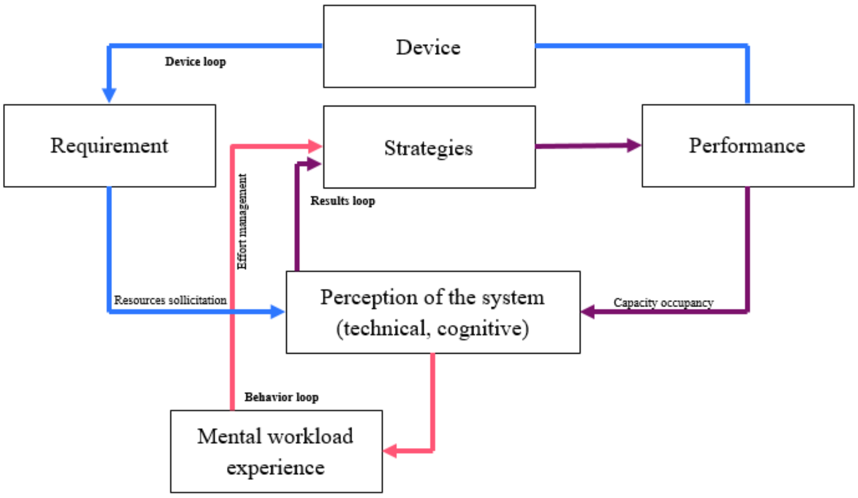


**Fig. 3.** Cegarra's model of mental workload [19].

### 2.4.2 Links with cognitive control modes

Cegarra's model shows that operators' mental workload depends on a set of external factors (e.g. time pressure, number of goals), and operators need to commit resources to deal with these factors. This feature leads to a modulation of attentional resources use. Similarly, Hollnagel [10] asserts that each cognitive control mode is related to a certain level of constraints that affect the level of attentional resources use. Table 2 shows these links.

**Table 2.** Links between the COCOM cognitive control modes, attentional resources use, and the level of constraints [9].

| *COCOM* mode | Attentional resources use | Level of constraints |
|---|---|---|
| Strategic | Medium-High | Low-Medium |
| Tactical attended | Medium-High | Medium |
| Tactical unattended | Low | Low |
| Opportunistic | High | High |
| Scrambled | Very High | Very High |

The level of constraints shows the combination of the external factors mentioned above. For example, if there are multiple goals to achieve in a limited amount of time, both the level of constraints and the use of attentional resources will be high; thus, we can assume that the opportunistic mode is instantiated. In contrast, if there is only one goal to achieve within ample time, we can assume that the tactical unattended mode is instantiated. The factors involved in the level of constraints seem to be line with those involved in Cegarra's mental workload model.

The use of attentional resources predicts the instantiated control mode. For example, Hollnagel describes the strategic mode as the "deliberate and careful planning of actions" that "cannot be achieved without paying attention" (p. 15) [10]. Similarly, the tactical unattended mode is instantiated when "people know what to do but may not bother follow it in detail" because "the situation is very familiar or there seems to be plenty of time" (p. 15) [10]; this explains the low attentional resources use. The level of attentional resources use thus appears to be equivalent to the level of constraints.

From these observations, we deduce that we can measure the mental effort of operators through physiological measurements, and analyze the external constraints. The combination of external constraints and mental effort provides information regarding the mental workload level experienced by operators. We hypothesize that this mental workload level can help us assess the cognitive control mode instantiated by operators, hence the quality of the decision-making process.

It would be possible to detect in real time the moments when the probability of the degradation of decision making increases. For example, if we measure a low level of mental workload in the cruise phase in the cockpit, which is a phase with a low level of constraints, we could expect that operators are in the tactical unattended mode. Hollnagel explains that this is a mode where performance failure may occur because of the false sense of safety procured by these situations [10]. Similarly, if we measure a high level of workload associated with a high level of constraints such as what happens during an unusual situation with high time pressure and multiple tasks, we can assume that operators will be in the opportunistic mode, not far from the scrambled mode that would be detected if the mental workload level becomes excessive.

## 3 Discussion

Our ultimate goal is to use different kinds of measures to have a real-time estimate of the operators' mental workload level. In their study, Young, Brookhuis, Wickens and Hancock [13] suggest that recent research in neurosciences offers the most promise to define thresholds for mental overload and underload. Many studies recommend the use of brain oxygenation metrics, which could represent a quantitative measure of attentional resources [20] [21]. Since attentional resources use can indicate the mental workload level in combination with the measurement of external constraints, we plan to use functional near-infrared spectroscopy (fNIRS) to assess the activity in the prefrontal cortex, which is correlated with mental workload in numerous studies [22] [23]. We also plan correlations with heart-rate variability [24] and ocular activity [25] [26] measurements.

We intend to conduct two experiments. The first one will take place in a laboratory and will help us calibrate and validate the measurement protocol of mental workload using the three indicators just mentioned. Participants will complete a multitasking computer activity with various levels of difficulty. This experiment will enable us to determine the mental overload and underload thresholds.

The second experiment will be more ecological. It will take place in a realistic flight simulator where we will measure pilots' mental workload in real time using different predefined scenarios. These scenarios will place pilots in complex situations defined through exhaustive cognitive work analysis and task analysis.

## 4 Conclusion and perspectives

This study of decision-making, cognitive control, and mental workload models has enabled us to highlight some similarities and links between these notions. In particular, it highlights the fact that the quality of decision making depends upon the cognitive control mode instantiated by operators. This control mode is the result of multiple factors (internal and external) and could be assessed by measuring the mental workload level in terms of the situation operators are facing.

The goal of these experiments is to be able to determine the cognitive control mode instantiated by pilots so as to explore innovative ways to assist pilots in their tasks to mitigate excessive mental workload levels. This could take the form of new kinds of assistance in the cockpit.

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