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The modeling of three levels of cognitive controls with the Cognitive-OODA loop framework

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Abstract

Designing decision aids suitable for C2 environments requires models with a sufficient level of cognitive granularity. With its low cognitive granularity level, the existing OODA loop commonly used to represent the C2 decision cycle cannot sufficiently support the design of decision aids. In an effort to increase its level of cognitive granularity, Breton and Rousseau [8] proposed the C-OODA loop. However, this model offered few details on the control criteria-based components that govern the quality of the state produced from each cognitive process and the information transfer between these processes.

The objective of this document is to address this problem by providing more details on these units and their parameters. From this, the modeling of different levels of information processing is done. This modeling effort provided the opportunity to identify potential cognitive strategies that can be used by decision-makers to overcome problems such as a high level of state uncertainty. These analyses yielded a list of cognitive processes and strategies that should be technologically supported in order to help novice and intermediate decision-makers to execute their tasks with an acceptable level of performance and to allow them to attain the expert level sooner and more easily.

Résumé

Le développement de systèmes d'aide à la décision pour les environnements de C2 doit se baser sur des modèles offrant une granularité cognitive adéquate. Avec son bas niveau de granularité cognitive, la boucle OODA communément utilisé pour représenter le cycle décisionnel en C2 ne peut influencer suffisamment le design de système d'aide. Dans un effort pour contrer ce problème, Breton & Rousseau [8] ont proposé la boucle C-OODA. Cependant, ce modèle offre peu de détails sur les composantes de contrôle qui gouvernent la qualité de l'état produit par chacun des processus cognitifs et le transfert d'information entre ces processus.

L'objectif de ce document est d'adresser ce problème en fournissant davantage de détails concernant ces unités et leurs paramètres. La modélisation de trois niveaux de traitement d'information permet l'identification de stratégies cognitives pouvant être utilisées afin de diminuer l'impact de hauts niveaux d'incertitude dans la situation. À partir de ces analyses, une liste de processus cognitifs et de stratégies pouvant être supportés par la technologie de façon à aider les novices et intermédiaires à exécuter la tâche avec un niveau acceptable de performance et leur permettre d'atteindre un statut d'expert plus rapidement a été élaborée.

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Executive summary

The modeling of three levels of cognitive controls with the Cognitive-OODA loop framework

Richard Breton; DRDC Valcartier TR 2008-111; Defence R&D Canada Valcartier; September 2008.

Introduction: The design of decision aids adapted to C2 environments needs to rely on models with a sufficient level of cognitive granularity. With its low cognitive granularity level, the actual OODA loop commonly used to represent the C2 decision-cycle cannot sufficiently influence the design of support systems. In an effort to increase its level of cognitive granularity, Breton and Rousseau (2005) proposed the C-OODA loop. This paper builds on Breton and Rousseau's work by providing more details on the cognitive processes included in the C-OODA, specifically on the role and the components included in the control criteria-based units.

The control criteria-based units include three sub-units: the quality control unit, the iteration usefulness control unit and the temporal control unit. Based on a speed/accuracy trade-off, the first unit intervening in the process will be either the quality control unit (emphasis on accuracy) or the temporal control unit (emphasis on time). The iteration usefulness control unit always follows the quality control unit. The quality control unit is based on the comparison between a current state (result of the process) and an expected state. This comparison yields a quotient of certainty. Each state produced from the processes included in the C-OODA phases has a specific quotient of certainty. The role of the iteration usefulness unit is to determine the usefulness of doing additional iterations in order to increase the value of the certainty quotient in terms of the cost of the additional iterations (the closer is to 1, the closer the current state is to the expected state). Finally, the temporal control unit determines the ratio between the time required for an additional iteration and the time available in the situation.

Results: Three different levels of information processing (novice, intermediate and expert) were modelled and compared in the C-OODA loop framework. Here are some findings.

- At the novice level, most certainty quotients are indefinable. The reason is that novices do not have sufficient domain knowledge to correctly establish what should be the expected state in a given situation. For the same reason, the usefulness of additional iterations is also indefinable. The time spent to execute each C-OODA phase at the novice level will be based on human dimensions like the feeling of knowing, personality traits (perfectionism), etc.
- At the intermediate level, decision-makers may possess sufficient domain knowledge to establish appropriate expected values. Controlled processing, which takes time and resources, is required to establish the familiarity of the situation. As soon as a familiar situation is defined, subsequent processes are automatic. However, a controlled evaluation of the pros and cons of the selected course of action can be performed.
- At the expert level, following a rapid but controlled detection of a very familiar situation, all subsequent processes are automatic. Note that the evaluation of pros and cons for the automatically triggered course of action is bypassed.

- Automatic processing is possible if the value of the quotient tends toward 1.
- Controlled processing is required if the value of the quotient tends toward 0.
- The value of the quotient is a subjective value calculated from the ratio between two other subjective values (levels of certainty of the current and expected states). It is therefore subject to human error.
- It is not possible to define a specific value at which the process could switch from controlled to automatic.

Significance: From the comparison between these three levels of information processing, the following potential design requirements were identified.

- Support is required to provide detectable data from the environment. Support should seek to increase the decision-maker's confidence in the data.
- Support is required to help novice decision-makers to define what an ideal state should be and to help intermediate decision-makers to determine the familiarity of the objects.
- Support is required to provide domain knowledge databases. It should also seek to reduce the workload in short-term memory related to complex situations (involving several objects). Automatic recognition systems (like case-based reasoning systems) could be considered.
- Technological devices for simulating situations over a given period of time (with a level of confidence provided) would be helpful. Such devices would also be useful for intermediate decision-makers to validate their assumptions.
- Inductive and deductive reasoning strategies should be supported with appropriate technological tools (i.e. case-based reasoning systems or computational models).
- Story building and mental simulation should be supported with technological tools that reduce the memory workload.

Future plans: The C-OODA loop described in this document includes a formalism element that could lead to the development of a computational model of the C-OODA loop. It would then provide valuable information on human information processing activities in complex environments such as C2. It could help bridge the gap between models proposed from a human factor perspective and solutions that are technologically driven.

Sommaire

The modeling of three levels of cognitive controls with the Cognitive-OODA loop framework

Richard Breton; DRDC Valcartier TR 2008-111; R & D pour la défense Canada – Valcartier; Septembre 2008.

Introduction: Le développement de systèmes d'aide à la décision adaptés aux environnements de C2 doit se baser sur des modèles offrant une granularité cognitive adéquate. Avec son bas niveau de granularité cognitive, le modèle classique de la boucle OODA communément utilisé pour représenter le cycle décisionnel en C2 ne peut influencer suffisamment le design de système d'aide. Dans un effort pour en augmenter sa granularité cognitive, Breton & Rousseau (2005) ont proposé la boucle C-OODA. Ce document se veut une extension du travail de Breton & Rousseau en fournissant plus de détails sur les processus cognitifs impliqués dans la boucle C-OODA et plus spécifiquement, sur le rôle et la constitution des trois unités de contrôle.

Les unités de contrôle inclus trois sous-unités: l'unité de contrôle de la qualité, l'unité d'évaluation de la nécessité d'itérations additionnelles, et l'unité de contrôle temporel. Basé sur un compromis vitesse/précision, la première unité en jeu peut être soit l'unité de contrôle de la qualité (emphase mise sur la précision) ou soit l'unité de contrôle temporel (emphase mise sur la vitesse). L'évaluation de la nécessité de d'autres itérations suivra toujours l'unité de contrôle de la qualité. Cette dernière est basée sur la comparaison entre la valeur de l'état de la situation actuelle et un état attendu. Cette comparaison conduit au calcul d'un quotient de certitude pour chaque état produit par un processus inclus dans une phase de la C-OODA. L'évaluation de l'utilité de faire d'autres itérations est basée sur l'augmentation potentielle du quotient de certitude avec chaque itération (valeur près de 1: état courant presqu'égal à la valeur attendue) en fonction du coût lié à ces itérations additionnelles. Finalement, l'unité de contrôle temporel évalue le ratio entre le temps requis pour une itération additionnelle et le temps disponible dans la situation.

Résultats: Trois niveaux différents de processus d'information (novice, intermédiaire et expert) ont été modélisés et comparés dans le contexte de la boucle C-OODA. Voici quelques observations:

- Au niveau novice, la plupart des quotients de certitude sont indéfinissables. Ceci peut être expliqué par le fait que les novices ne possèdent pas suffisamment de connaissances du domaine leur permettant d'établir correctement qu'est-ce qui devrait être attendu dans une situation particulière. Pour la même raison, l'utilité de faire des itérations additionnelles est aussi indéfinissable. Le temps passé au processus de l'information pour chaque phase de la C-OODA sera fonction de dimensions humaines telles que le sentiment de savoir ou des traits de personnalité tels que la confiance en ses moyens et le perfectionnisme.
- Au niveau humain, le décideur peut posséder assez de connaissances du domaine pour établir de façon appropriée les valeurs attendues. Des processus contrôlés prenant du temps et des ressources sont requis pour établir le niveau de familiarité de la situation. Aussitôt qu'une situation familière a été reconnue, les processus subséquents sont automatiques. Cependant, une évaluation contrôlée des avantages et inconvénients reliés à la suite d'actions sélectionnée peut être faites.

- Au niveau expert, suivant une reconnaissance rapide mais contrôlé d'une situation familière, tous les processus subséquents sont automatiques. Notez que l'évaluation des avantages et inconvénients de la suite d'actions n'est pas effectuée.
- Un processus automatique est possible sur la valeur du quotient de certitude tend vers 1.
- Un processus contrôlé est requis si la valeur du quotient de certitude tend vers 0.
- La valeur des quotients est subjective et est calculée à partir d'un ratio entre deux autres valeurs jugées subjectivement. Ainsi, ces valeurs sont sujettes à l'erreur humaine.
- Il n'est pas possible de définir une valeur à partir de laquelle on passe d'un processus contrôlé à un processus automatique.

Importance: À partir de la comparaison entre les trois niveaux de processus d'information, quelques requis en design peuvent être identifiés:

- Un support est requis afin de fournir à l'usager des données détectables dans l'environnement. Ce support technologique devrait permettre d'augmenter le niveau de confiance de l'usager par rapport aux données en présence.
- Un support est requis afin d'aider les novices à définir que devrait être l'état attendu dans une situation donnée et d'aider les intermédiaires à évaluer plus efficacement la familiarité des objets.
- Un support est requis afin de fournir des bases de données reliées au domaine en présence. Ceci permettrait de réduire la charge mentale imposée aux usagers (par rapport à la mémoire à court terme) en présence de situations complexes impliquant beaucoup de données. Des systèmes de reconnaissance automatique (systèmes basés sur le raisonnement par cas) pourraient alors être considérés.
- Des systèmes technologiques permettant la simulation de l'évolution d'une situation dans le temps seraient également utiles. De tels systèmes seraient utiles pour permettre aux intermédiaires de valider leurs hypothèses élaborées pour expliquer la situation.
- Les systèmes d'aide devraient supporter le raisonnement inductif et déductif (exemple: systèmes basés sur le raisonnement par cas ou modèles computationnels).
- Les stratégies de construction d'histoires et de simulation mentale devraient être supportées avec des technologies permettant la réduction de la charge de travail mentale imposée en mémoire par l'utilisation de ces stratégies.

Perspectives: La boucle OODA décrit dans ce document inclus un effort de formalisme pouvant conduire au développement d'un modèle computationnel. Ce modèle fournirait alors de l'information utile sur les processus impliqués dans des environnements complexes tels que C2. Ce modèle pourrait contribuer à rapprocher les modèles proposés à partir de recherches en facteurs humains et les solutions qui sont basées sur la technologie.

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1 Introduction

Command and control (C2) can be characterized as a dynamic human decision-making process. In military documents, the C2 decision cycle is commonly represented with the OODA loop (Observe-Orient-Decide-Act) proposed by Boyd [1]. For instance, in the US Navy doctrine document (NDP 6) on C2 [2], the OODA loop is given a central position as the basis for describing the Decision-Execution cycle in C2. Similarly, US Army Field Manual 6.0 (FM 6.0) [3] considers the OODA loop to be a valuable tool for illustrating a commander's decision-making processes, albeit admittedly simplistic. This simplistic representation may explain the popularity of the OODA loop for depicting the C2 decision cycle. However, such low-level representation can also be considered as its major weakness when taken to provide information on the processes that sustain the decision task [4]. This may be even more problematic if such a simplified model is taken as the theoretical foundation for the identification of design requirements for the development of support systems. Identifying design requirements requires at least a minimum level of cognitive granularity in the model.

Increased cognitive granularity in a model often comes at the cost of greater complexity in the representation. In addition, in the alternatives proposed to remedy the flaws in the OODA loop, the modifications often focus on a specific component of the loop, which most of the time is Orient [5, 6, 7]. The result typically is a more complex and disproportionate representation of the loop than the classic model proposed by Boyd.

Breton and Rousseau [8] have developed a cognitive version of the OODA loop, the C-OODA loop, which considerably increases the level of cognitive granularity of the first three phases of the loop (Observe, Orient and Decide) without increasing too drastically the level of complexity of the representation. To reach that objective, Breton and Rousseau used the modular approach proposed by Rousseau and Breton [4, 9] with the M-OODA model. The M-OODA loop represents each OODA phase with a basic module as illustrated in Figure 1. The M-OODA shares with the classic OODA its sequential module operation. In such a model, the output of each module is strictly linked to the input of the next. According to Rousseau and Breton, it is that output/input connection that enables the M-OODA cycle to operate sequentially. However, since it allows feedback between modules, the M-OODA model does not suggest a unique sequential and unidirectional processing. The M-OODA loop provides a powerful means to represent dynamic control in the C2 decision cycle, but it still operates at the low level of cognitive granularity that is a limitation of the classic OODA [8]. Hence, the C-OODA cycle was developed in order to increase the level of cognitive granularity of the loop while using the simple M-OODA architecture as a framework.

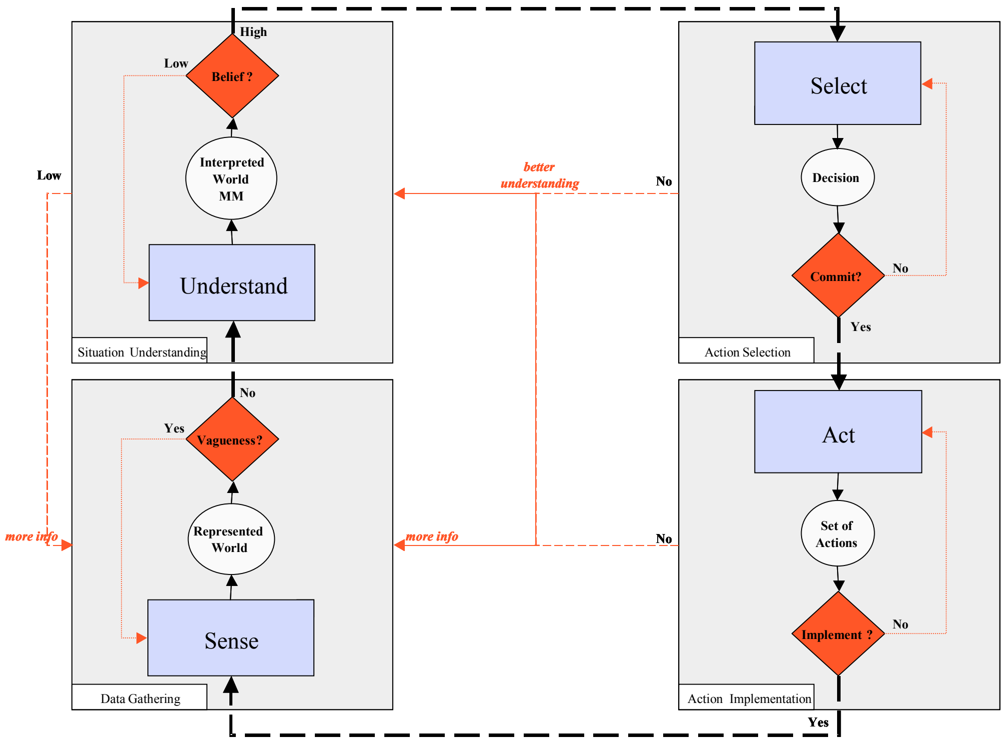

Figure 1: The M-OODA loop proposed by Rousseau and Breton [4, 9].

2 The C-OODA loop

Breton and Rousseau [8] suggest that the increase in cognitive granularity in the first three phases of the C-OODA loop should be based on known cognitive theories and models. They purposely skip the modeling of the Act phase, claiming that a decision is already made and the processes included in the Act phase may call for different skills and resources. Including the modeling of the Act phase in the M-OODA loop would drastically increase its complexity without adding much knowledge about the decision-making process.

To model the first three phases of the C-OODA loop, the following theories were used to increase cognitive granularity:

- Observe: feature integration theory [10];
- Orient: theory of situation awareness [11];
- Decide: recognition-primed decision model [12, 13, 14].

A further enhancement in the Breton and Rousseau C-OODA model is its control component. The control component represents uncertainty as to the state resulting from the process. It also includes three subcomponents:

1. uncertainty as to state clearness;
2. uncertainty as to the usefulness of further iterations to improve the state quality;
3. uncertainty as to the time remaining in the situation for further iterations.

These three subcomponents included in the control component of the C-OODA may contribute to the representation of different levels of control.

2.1 Modelling the Observe phase

Treisman's feature integration theory [10] suggests a two-stage process in which salient features of stimuli are detected automatically by independent feature modules (i.e., colour, size, distance, etc.) and integrated in the second stage to form a unitary object. These objects become the basic elements of information considered in the decision cycle.

Treisman's theory suggests that the detection of features is cognitively automatic while their integration is controlled. This mean the Observe phase of the OODA loop can be decomposed into two generic cognitive processes. These cognitive processes and the resulting state and type of uncertainty are presented in Table 1.

Table 1: Processes, states and types of uncertainty in Observe phase of C-OODA loop.

Processes	States	Types of uncertainty
Perceiving: the perception of features in the environment	**Features**	**Feature clearness**
Feature matching: the process of matching features perceived in the environment with knowledge stored in the memory	**Structured objects**	**Object familiarity**

2.2 Modelling the Orient phase

The theory of situation awareness (SA) proposed by Endsley [11] is used to provide theoretical foundations for increasing the level of cognitive granularity of the Observe phase. Traditionally, the Observe phase has been associated with the understanding of a given situation. The SA theory was developed to represent the assessment process that leads to awareness of a given situation. Consequently, there is a theoretical link between the objective of the Orient phase and Endsley's theory.

In her model, Endsley proposes a three-step process involving the perception of elements in the environment, the comprehension of the current situation, and their projection in the future status of the situation. While the first process (perception) can easily be linked to the Observe phase, the other two processes (comprehension-projection) underscore the importance of understanding the situation and being able to project its evolution in the future. The quality of the execution of this latter process is crucial to achieving appropriate control in the situation. Therefore, from a theoretical standpoint, the last two processes included in the SA theory can be used to define the Observe phase of the C-OODA loop. These cognitive processes and the resulting state and type of uncertainty are presented in Table 2.

Table 2: Processes, states and types of uncertainty in Orient phase of C-OODA loop.

Processes	States	Types of uncertainty
Comprehending: Linking the structured objects together to form a comprehensive picture of the situation	**Causality links**	**Causality logic**: Validate causal links between objects
Projecting: The mental projection of potential evolutions of the situation	**Mental model**: The establishment of causality links and the projection of future status of the situation lead to the development of a mental model for the situation	**Temporal certainty**: Validate the situation evolution from a temporal perspective

2.3 Modelling the Decide phase

Although there are strong links between SA and decision-making, Endsley [15] states that it is important to recognize the two processes as being independent. In one study, Breton and Rousseau [16] claimed that, because of its naturalistic characteristics, the recognition-primed decision (RPD) model elaborated by Klein [12, 13, 14] is more suitable than other descriptive or normative decision-making models for representing the C2 decision cycle. Murphy and Glasgow [17] arrive at the same conclusion and propose an RPD version of the OODA loop.

Hence, in the C-OODA loop proposed by Breton and Rousseau [8], the RPD model is used to provide cognitive details to increase the granularity of the Decide phase. The naturalistic approach espoused in this model makes it applicable to the dynamic, time-stressed and uncertain situations inherent to C2 environments. One benefit with the RPD model is that it represents the different levels of processing from which individuals with specific levels of expertise can execute the C2 decision cycle. It is based on the premise that novices and experts should execute the task in different ways. RPD stipulates that rather than weighing the advantages and disadvantages of several alternatives, decision-makers use their experience to make an appreciation of a situation and develop a solution or course of action (COA) on the first try. Consequently, the RPD model gives the individual's level of expertise a central role in task execution. Incorporating RPD concepts into the C-OODA loop enables this model to take account of differences in levels of processing of novices and experts.

The Decide phase of the OODA loop can therefore be decomposed into the two generic cognitive processes listed in Table 3 with their resulting states and types of uncertainty.

Table 3: Processes, states and types of uncertainty in Decide phase of C-OODA loop.

Processes	States	Types of uncertainty
Recalling: Central to the RPD model is the recalling of prototypical actions	**Prototypical actions**	**Plausibility of action**: Validate if the prototypical actions recalled are plausible in the situation
Evaluating: Evaluating the prototypical actions against expectations, goals, etc.	**List of Pros and Cons**: The establishment of causality links and the projection of future status of the situation lead to the development of a mental model for the situation	**Story optimistic**: Evaluate if the story built from story building mental processing is optimistic in the situation, in light of the pros and cons of the potential story

2.4 C-OODA architecture

Figure 2 presents the resulting C-OODA loop proposed by Breton and Rousseau [8]. Note that, to minimize the complexity of the representation, they modified the structure of the M-OODA model. The result is a layered representation that goes from the bottom to the top. Each OODA phase is represented with two layers that include the component of the basic module (Process-State-Control) of the M-OODA.

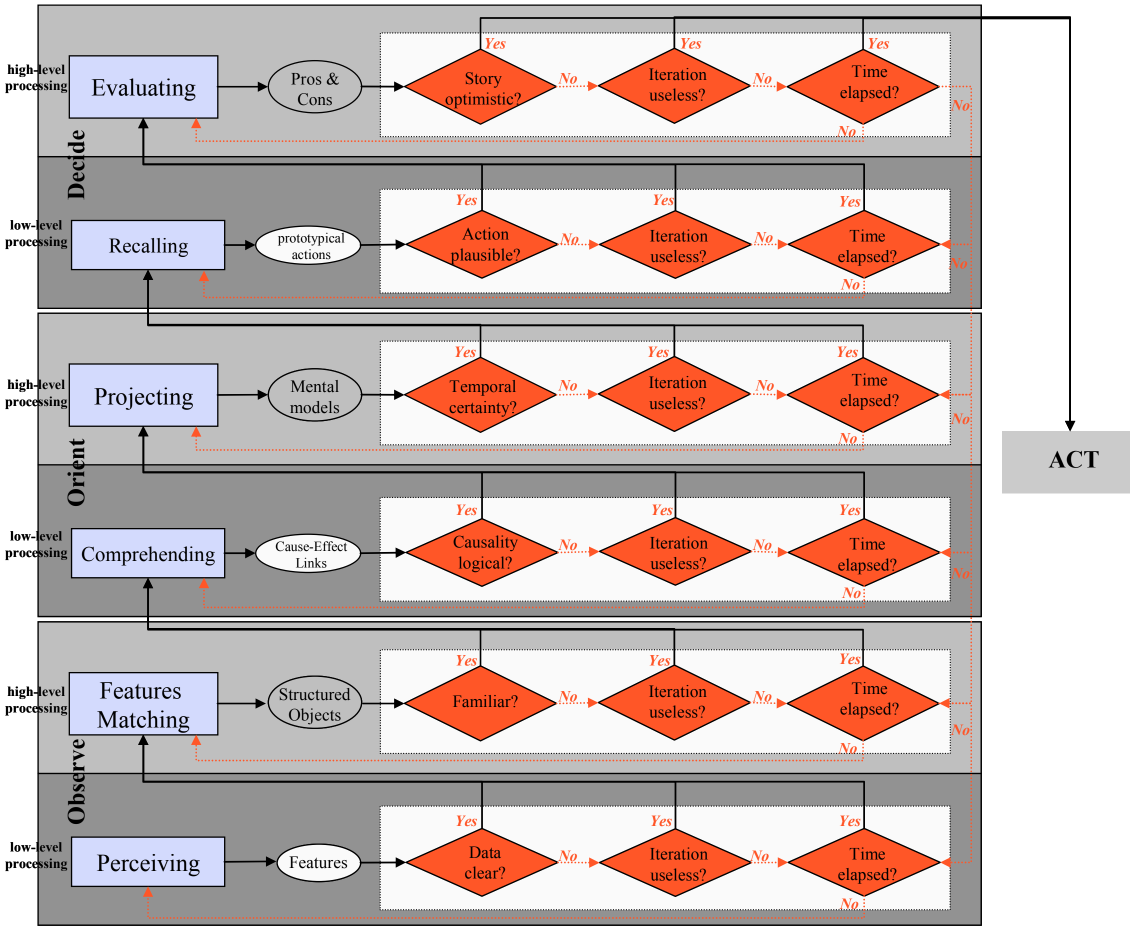

Figure 2: The C-OODA loop proposed by Breton and Rousseau [8].

The lower layer represents the low-level processing of the phase (Perceiving-Comprehending-Recalling), and the upper layer represents the higher-level processing (Features Matching-Projecting-Evaluating). Each phase follows the same structure in order to minimize the complexity of the representation. As in the M-OODA model, feedback and feed-forward loops are included within and between layers to represent the dynamic aspects of C2.

2.5 Impact of level of expertise in the C-OODA loop

The modeling of the C-OODA loop with the concepts imported from these theories and models underscores three important elements in a decision-making task:

- In the Observe phase of the loop, a critical process is the integration of the elements of the environment into a structured object. The level of familiarity of this object will be a determining factor in the execution of the subsequent processes in the loop.

- In the Orient phase, the capacity to predict the status of the element in the situation will influence the achievement of control of this situation. Obviously, there is a strong link between the level of familiarity of the objects built from the Observe phase and the capacity to accurately predict the evolution of the situation.
- The critical element in the Decide phase is the level of expertise of the decision-maker. Experts have knowledge that allows them to decide rapidly.

It is interesting that expertise can be seen as the element that connects the three phases. The level of expertise will determine the capacity to judge the familiarity of an object and, obviously, to predict its status in the future. Klein [12, 13, 14] also underscores the importance of the level of expertise in the selection of a decision-making type of execution. Rasmussen [18, 19] with his Skills-Rules-Knowledge model (SRK) also proposed three levels of activity control based on the level of familiarity of the situation.

Whatever the level of the decision-making task (novice, intermediate, expert), information needs to be perceived, understood, projected, evaluated, etc. The distinction should be more in the speed of the execution of these processes based on the level of familiarity of the situation. For instance, highly familiar situations would call for automatic processing, where minimal attentional and cognitive resources are devoted. Conversely, new situations would call for controlled processing, which takes time and attentional resources.

Obviously, there is a strong link between level of familiarity, level of expertise and level of processing. Experts will encounter more familiar situations and then process information more automatically. Conversely, a novice will encounter new situations more often and then deal with the situations through controlled processing.

In this document, we use the C-OODA model to illustrate three levels of information processing (novice, intermediate and expert). More specifically, we will demonstrate that the distinction between these three levels of processing lies in the criteria-based control component of the C-OODA. Initially proposed as a single unit in the M-OODA model [4, 9], in the C-OODA loop the criteria-based component is decomposed into three distinct units [8] as follows:

- One unit is related to the quality of the state produced from each process (its level of uncertainty);.
- Another concerns the usefulness of doing more iterations to improve quality. This control unit is based on the ratio between the quality improvement and the cost of additional iterations (time and resources).
- The third unit addresses the temporal aspect of the situation by imposing time constraints on process execution.

The next sections provide a more detailed cognitive description of these three sub-units than that offered in the Rousseau and Breton [4, 9] and Breton and Rousseau [8] papers. These sections are followed by the modeling of the three levels of decision-making tasks (novice, intermediate, expert processing) with the C-OODA loop. The distinction between these decision-making task levels places emphasis on the control criteria-based units.

3 Control criteria-based component of C-OODA loop

As suggested in the preceding section, the distinction between the novice, intermediate and expert decision-making processes could be established from the control criteria-based component. At one end of the continuum, several iterations of each C-OODA layer should be required by a novice decision-maker to reduce uncertainty in the decision-making process. At the other end, experts faced with highly familiar and therefore fairly certain situations should not require multiple iterations of the C-OODA phases. Instead, layers of the model should be performed with minimal attentional resources and time. The next subsections present the criteria-based control units.

3.1 Quality control unit

Breton and Rousseau [8] suggest that the quality control unit regulates the iteration process that improves the quality of the state. The quality of the state needs to be related to its level of uncertainty. According to Levis and Athans [20], the unifying concept in C2 is the need to cope with uncertainty. The literature offers a variety of uncertainty classifications and definitions [for details see 21, 22, 23, 24]. Breton, Rousseau and Price [25] offer an interesting classification of the different types of uncertainty based on the OODA loop phases. In their classification, the uncertainty type related to the Observe phase is vagueness (i.e. missing or ambiguous data). In the Orient phase, uncertainty is defined as the degree of belief in the situation (i.e. plausibility). In the Decide phase, uncertainty concerns the commitment of assets to a course of action (i.e. availability of resources to execute the plan, alternate courses of action, etc). In the Act phase, the uncertainty mostly concerns the feasibility of implementing the selected course of action.

Tables 1, 2 and 3 (pp. 3, 4, 5) show the nature of the state related to each C-OODA process and the nature of the quality control unit. While the nature of the state is related to the cognitive process in play (defined from well-known cognitive theories and models), the nature of the uncertainty is based on the classification put forward by Breton et al [25].

In the Observe phase, the uncertainty is related to both data clearness and the familiarity of the decision-maker with the object, which results from the integration of the different features perceived in the environment. The role of the quality control unit is to evaluate the data clearness and the resulting familiarity of the decision-maker with the object. In the Orient phase, the uncertainty concerns the logic behind the cause-effect links between the structured objects and their temporal relationships. While in the first phase (Observe), the uncertainty concerns the objects and their relation with the decision-maker, in the second phase, it concerns the mental models that include the relationships (space and time) between the objects. These relationships represent a picture of the situation. In the third phase, the uncertainty is related to the potential actions (plausibility and probability of success).

A parallel can be drawn between the functioning of the quality control unit in the C-OODA loop and the perceptual control theory (PCT) of Power [26]. In PCT, the presence of feedback is essential for the control of goal-directed human activity. Actions are set to reduce the discrepancy between the human expected state or goal and the perception of the actual situation. PCT also suggests the concept of control loop. Given sufficient time, appropriate learning to build a robust mental model of the situation, and the application of required actions, PCT predicts that the error signal representing the discrepancy between the expected and actual states would eventually approach zero if the control loop remains unbroken.

In the C-OODA, the role of the quality control unit is to regulate the quality level of the state based on standards that are internally imposed (similar to the expected state in PCT) or externally imposed (for instance, defined from command intent) (see Figure 3). Each process included in the C-OODA layers produces a given state (current state). As in PCT, the quality control unit determines the difference (Σ = error value) between the quality level of the state and the expected level (the expected state). The difference between the two states defines the level of quality of the current state. The smaller the error, the higher the quality. When the quality level is judged unacceptable, an iteration process is required to reduce the error value.

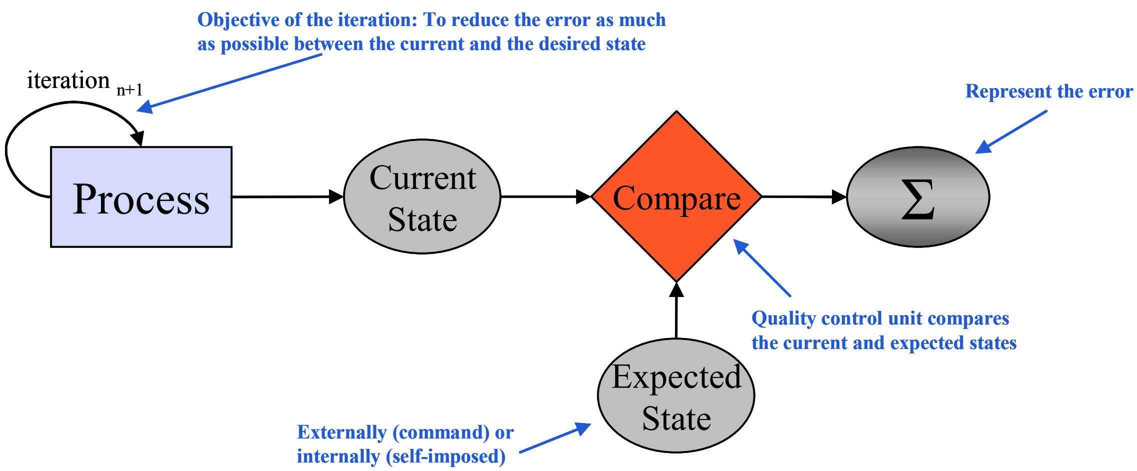

Figure 3: The quality control unit processing.

This view underscores the importance of subjective judgment. In fact, these values represent more the state of mind of the decision-maker than the actual uncertainty value related to a given object in the environment. Therefore, the notion of subjectivity is crucial in the establishment of these values.

- **The effect of subjective judgment in the establishment of the expected state**: Subjective judgment obviously intervenes in the establishment of the expected state. The expected state is based on the environmental constraints. However, subjective judgment happens in the interpretation of the expectations. The expected state may be established from the person's comprehension of what is required in the situation. Whether imposed internally or externally (command), the expected state will be the perception of or judgment as to what the state should be. Hence, the quality of the judgment as to what the expected state should be will directly affect the process. For instance, effective communication processes will be required to ensure that the expected state stated by one person (i.e. commander) is clearly understood by the other (subordinate). Discrepancy between the expected state formulated by the commander and the one understood by his subordinate could result in ineffective information processing and sharing.
- **The effect of subjective judgment in the establishment of the current state**: The current state is the result of the person's processing. Consequently, it will be influenced

considerably by the quality of the processing and the person's level of expertise and skills. Such level of expertise and skills will necessarily influence the way objects are perceived (top-down approach). Accordingly, the establishment of the current state is the result of subjective judgment.

The comparison process depicted in Figure 3 includes the calculation of a ratio (between the expected and current states) for all types of uncertainty included in the C-OODA. To better represent this, let's take a simple modelling approach described as follows.

For the Observe phase: level of data clearness (clear value) $\in [0, clear_{max}]$

$Clear_{max}$ is an expected value, so

$clear_{expected} = clear_{max}$

Quotient of clearness (Q_{clear}) = clear value/$clear_{expected}$

and $Q_{clear} \in [0, 1]$

For the Observe phase: level of familiarity (fam value) $\in [0, fam_{max}]$

Fam_{max} is expected value, so

$fam_{expected} = fam_{max}$

Quotient of familiarity (Q_{fam}) = fam value/$fam_{expected}$

and $Q_{fam} \in [0, 1]$

For the Orient phase: level of logic between the object (log value) $\in [0, log_{max}]$

Log_{max} is expected value, so

$log_{expected} = log_{max}$

Quotient of logic (Q_{log}) = log value/$log_{expected}$

and $Q_{log} \in [0, 1]$

For the Orient phase: level of temporal certainty (temp value) $\in [0, temp_{max}]$

$Temp_{max}$ is expected value, so

$temp_{expected} = temp_{max}$

Quotient of temporal certainty (Q_{temp}) = temp value/$temp_{expected}$

and $Q_{temp} \in [0, 1]$

For the Decide phase: level plausibility of recalled actions (plau value) $\in [0, plau_{max}]$

$Plau_{max}$ is expected value, so

$plau_{expected} = plau_{max}$

Quotient of plausibility (Q_{plau}) = plau value/$plau_{expected}$

and $Q_{plau} \in [0, 1]$

For the Orient phase: level of COA optimism (optimism value) $\in [0, optimism_{max}]$

$Optimism_{max}$ is expected value, so

$optimism_{expected} = optimism_{max}$

Quotient of optimism ($Q_{optimism}$) = optimism value/$optimism_{expected}$

and $Q_{optimism} \in [0, 1]$

3.2 Iteration usefulness control unit

As mentioned in the previous subsection, when the quality level (defined by the quotient parameter Q) does not reach an acceptable level, iteration are required to bring the Q closer to the optimal value of 1. The Q value can be seen as a measure of uncertainty based on the gap between the current state and expected state (error value Σ). Q values approaching the value 1 should characterize current states with less uncertainty. Conversely, Q values closer to 0 should be typical of highly uncertain states. Smithson [27] suggests that the prescription for coping with uncertainty in traditional and modern treatments of the subject is:

> "First, reduce ignorance as much as possible by gaining full information and understanding (obtained with more iteration)... Second, attain as much control and predictability as possible by learning and responding appropriately to the environment (reached with an appropriate level of expertise)... Finally, wherever ignorance is irreducible (no significant improvement with additional iterations), treat uncertainty statistically."

In other words, iterations are useful if they significantly reduce the gap between the current state and expected state. Following Smithson's advice, it is beneficial to treat iteration usefulness statistically in our approach. To do so, let's take these parameters:

- the uncertainty level associated with the state after a given iteration (n);
- the uncertainty level associated with the state after an additional iteration (n+1);
- the error (Σ) reduction representing the value of the diminution of the uncertainty with the additional iteration;

As is the case for the establishment of the current and expected states, subjective judgment will play a major role in the calculation of the error reduction value:

- **The effect of subjective judgment in the calculation of the error reduction value**: Σ represents the difference between two values that have been set subjectively. Since these two values are subjective, their related uncertainty level is necessarily subjective.

As is the case in statistical regression analysis, the uncertainty reduction value must represent a significant part of the uncertainty level associated with the state. As suggested by Smithson, uncertainty should be treated statistically. Therefore, the usefulness of additional iterations should follow the laws that govern statistical analysis. Iteration should be judged useful if the resulting reduction represents a significant part of the uncertainty. Accordingly, a ratio that considers the following parameters should be defined.

State Uncertainty Reduction (StateUncRed) = $\text{StateUnc}_{\text{iteration N+1}} - \text{StateUnc}_{\text{iteration N}}$

StateUncRed $\in [0, \infty]$

Quotient of Usefulness (Q_{useful}) = $\text{StateUncRed}/\text{StateUnc}_{\text{iteration N}}$

$Q_{\text{useful}} \in [0, 1]$

Consequently, as Q_{useful} approaches the value 1, iterations are judged useful.

As is the case for the other parameters, the notion of subjectivity is crucial in the establishment of these values.

- **The effect of subjective judgment in the estimation of the level of Σ reduction with an additional iteration**: The role of the iteration process is to reduce the Σ value. Without time constraints, the iteration process could go on as long as a significant reduction of Σ is obtained. As mentioned above, Σ is a subjective value. Hence, the evaluation of the potential reduction in Σ with additional iterations is necessarily a subjective judgment process, affected as it is by factors such as level of expertise, personality traits (e.g. perfectionism or level of confidence), or problems such as the feeling of knowing.

Obviously, level of expertise is a determining factor in subjective judgments. Experts possess more knowledge than novices in a variety of situations, so these situations are more familiar to experts. Experts should more easily understand the expectations of the situation (expected state), more effectively establish the current state (thereby reducing the Σ value), more easily estimate the level of Σ reduction with additional iterations, and more accurately estimate the costs to be incurred by additional iterations.

Note that the notion of usefulness represents an important distinction between the control aspect in the C-OODA loop and the control aspect proposed in PCT. In C-OODA, a potential gain in quality may be achieved through an additional iteration. But if the gain is not worth it, the iteration process is stopped.

In the C-OODA loop perspective, the state resulting from a given phase is not necessarily the optimal one (the state can still have a significant amount of uncertainty). In that sense, this view is in line with the one proposed in the RPD model. Klein [12, 13, 14] suggests that the decision resulting from the RPD processes can be seen as the best alternative possible based on decision-maker expertise in order to conform to the environmental constraints. Hence, in the C-OODA loop model, the resulting state of each phase should be the one that represents the best alternative possible in order to conform to the environmental constraints.

3.3 Temporal control unit

The third subcomponent is related to the time available in the situation. There is a need to make a distinction between **time constraint**, **time pressure** and **time urgency**. Time constraint is the restricted period itself (not the feeling). For Rastegary and Landy [28], a time constraint is the difference between the time available in a situation and the time required to perform a task. Jobidon, Rousseau and Breton [29] have proposed a model of action control, COCOM-T (Contextual Control Model – Temporal), based on Hollnagel's work [30, 31] and the concept of time constraint. In their model, Jobidon et al suggest that the action control mode is based on the ratio between the time available in the situation and the time required to achieve control. These two temporal parameters are subjectively evaluated by the individual during the situation. A reactive mode is used when the subjective time required to achieve control is longer than the subjective time available in the situation. When this latter parameter is longer than the subjective time to achieve control, more strategic behaviours are used.

There is a distinction between a time constraint and the feeling of being pressed to execute a task properly. This feeling is interpreted as time pressure. Time pressure may be variable from one situation to another and from one person to another. For instance, in a given situation with a specific time constraint, two individuals may not have the same feeling about the time pressure.

Finally, time urgency refers to an internally imposed time pressure. In other words, people impose on themselves the obligation to accomplish more and more tasks in an ever-shorter amount of time [32]. Therefore, time urgency may induce the same feeling (time pressure) as a specific time constraint. For purposes of distinction, time constraint may be seen as an external constraint while time urgency is an internal constraint.

With the context of the C-OODA loop and its temporal control unit, the concept that fits best is certainly time pressure. Time pressure implies a subjective interpretation of time constraints. Theoretically, the iteration process is allowed if the time required to execute the additional processing is shorter than the time available. But in practical terms, it is the delta (Δ) between the time judged to be required for the additional iteration and the time judged to be left in the situation. Obviously, if external timing devices are available, the Δ value will involve the externally stated time constraint and the time judged to be required to execute the additional iteration. This means there is still an important subjective judgment component in this process. Obviously, factors such as expertise and the capability to cope with time stress will play a major role in the temporal unit. Figure 4 represents the role of the temporal unit.

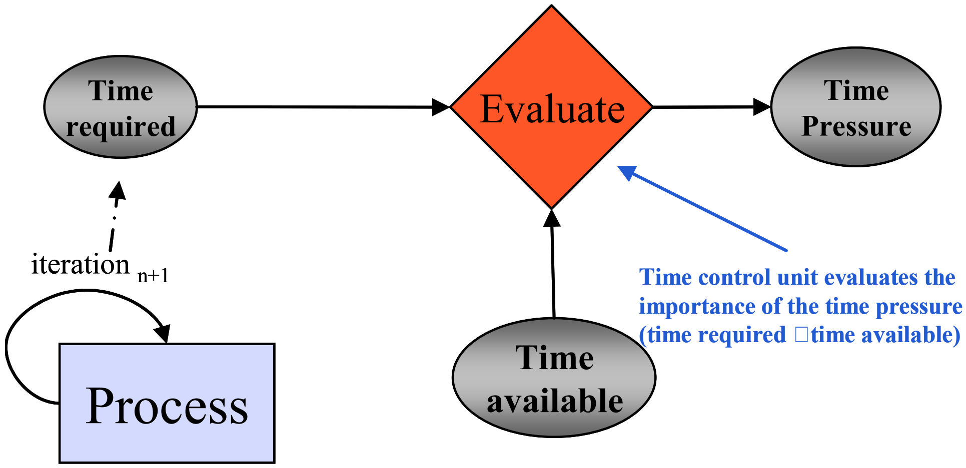

Figure 4: The time control unit processing.

The delta defining the time pressure factor (TP value) can be calculated from these formulas:

Time Pressure = Time Required – Time Available

Time Pressure $\in [-\infty, \infty]$

Clearly, the time pressure factor will decrease as the value of delta decreases. Iteration would be possible if the delta value is ≤ 0 (time required is equal to or shorter than the time available).

In complex and dynamic environments such as command and control, time and uncertainty factors are ever-present. They will have a huge impact on the quality of information processing. The relationship between uncertainty and time pressure has often been described as the speed/accuracy trade-off. The next subsection describes the relationships between the three criteria-based control units in the context of this trade-off.

3.3.1 Relationships between units: the Speed/Accuracy trade-off

Although Breton and Rousseau [8] never claimed that they were functioning sequentially, the representation of the three control criteria-based units included in the C-OODA loop suggests sequential processing (see Figure 2, p. 6). According to the model representation, the first criterion considered would be the one related to the quality of the state. The second one would concern the usefulness of doing further iterations to improve the state level of certainty. The third criterion would be based on the time available in the situation.

In this document, we suggest that the sequential order to the criteria is not fixed. Instead, the order in which they intervene in the phase execution should be related to the result of a speed/accuracy trade-off. Such trade-off should be based on the constraints in the situation. For instance, if time pressure is not important in the situation, then the emphasis should be put on quality. Conversely, in time-pressed situations, the temporal dimension could be the most important criterion to end the process. Hence, the sequential order of the control units should be adaptable to the environmental constraints. Figure 5 presents the sequential order according to the speed/accuracy trade-off.

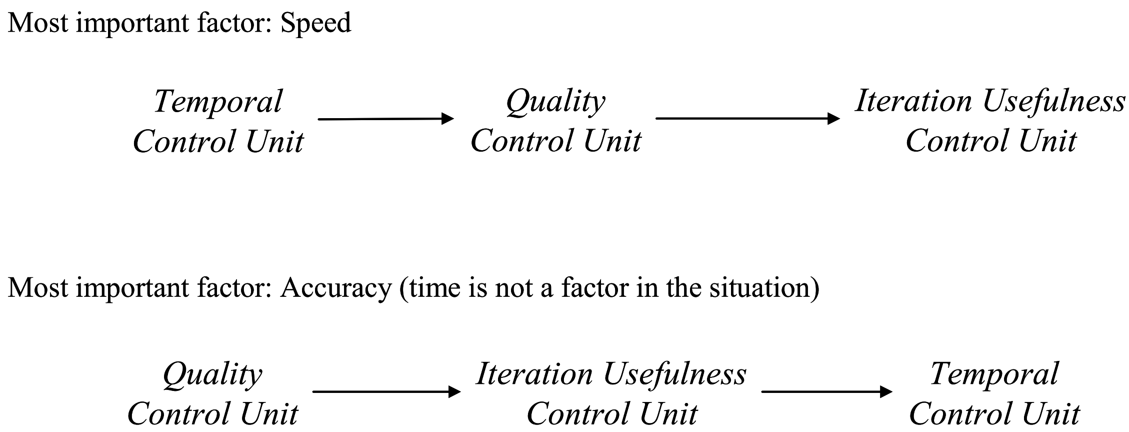

Figure 5: Sequential structure of the control units according to the speed/accuracy trade-off.

4 Modelling different levels of a decision-making task

Expertise plays a central role in the connection of the different elements in the C-OODA phases. With its theoretical foundations, the C-OODA loop offers an interesting model to represent different levels of decision-making that are mainly determined from the decision-maker's level of expertise. But as mentioned above, while they decompose the control component into three subcomponents, Breton and Rousseau [8] do not provide enough details on the nature of these subcomponents. We addressed that problem in the preceding subsections. Now we will make the distinction between levels of decision-making (novice-intermediate-expert) in regard to the control criteria units included in the C-OODA model.

Clearly, there is a need to understand how experts and novices make decisions or process information. It is important to understand the difference in processing between experts and novices in order to develop training programs that rapidly and efficiently raise novices to the expert level. Such fundamentals would also influence the development of support systems that can adapt to the decision-maker's level of expertise. The next section describes the levels of processing.

4.1 Levels of information processing

The term **human information processing** captures the idea that information or inputs from the environment are transformed through different mental processes. Atkinson and Shiffrin [33] offer a three-store model in which stimuli are received as inputs and transformed into outputs. The transformation process is supported by three processors (sensory register, short-term store and long-term store). According to this classic model, the sensory register processor records early visual and auditory stimuli (presumably before they are recognized). Once given attention, they are transferred to the short-term store for a relatively short period of time. The information held in the short-term store can be recorded as knowledge in the long-term store with appropriate mental processing (i.e. rehearsal). The Atkinson and Shiffrin model became the foundation for many research studies in cognitive psychology.

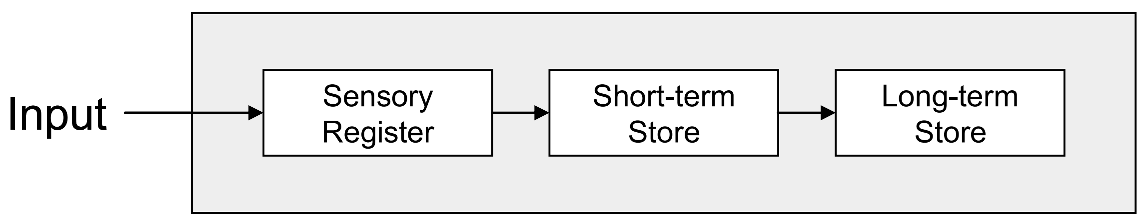

Figure 6: Information processing model proposed by Atkinson and Shiffrin [33].

More recently, Parasuraman, Sheridan and Wickens [34] proposed a four-stage model of human information processing. While the Atkinson and Shiffrin model presents the structure that supports human information processing, the model put forward by Parasuraman et al. shows the cognitive functions included in human information processing activities. The first stage of their model concerns the acquisition and registration of multiple sources of information. In this stage they include positioning and orienting of sensory receptors, sensory processing and initial pre-processing of data, prior to full perception and selective attention. The second stage includes cognitive operations prior to the decision point, such as rehearsal, integration and inference. In the Parasuraman et al. model, decisions are reached in the third stage and the decision is implemented in the fourth. Note that the Parasuraman et al. conception of human information processing is totally compatible with the classic version of the OODA loop. It also includes the same processes as the C-OODA model proposed by Breton and Rousseau [8].

The classic Atkinson and Shiffrin model illustrated in Figure 6 suggests a bottom-up processing perspective. Parasuraman et al. suggest the concept of "perception-action" cycles for their model instead of a strict serial sequence. This latest conception may be more coherent with many situations where information from the environment is processed from a top-down perspective. Top-down processing is happening when relevant-domain knowledge previously stored in the long-term memory is intervening in the processing of new information.

4.1.1 Impact of expertise on level of processing

A domain expert has specific knowledge that facilitates the processing of new information. Novices lack that knowledge. Expertise and learning are obviously linked. Anderson [35] proposes three stages of learning or skill acquisition. In the first—the cognitive stage—knowledge is primarily declarative and must be interpreted. At this stage, general problem-solving strategies are employed. In the second—the associative stage—problem-solving is transitioning from general methods to methods related to a specific domain. By the third stage, called the autonomous stage, knowledge is procedural, and is compiled, fast and error-free [36, 37]. Thus, the development of expertise in a specific domain could be the result of an associative process that connects the relevant concepts and knowledge stored in the long-term memory. For Banbury, Croft, Macken and Jones [38], the contention that experts are able to restructure their knowledge (e.g., chunking) and adopt skilled memory strategy (e.g., prioritization) to mitigate the load on their short-term memory when engaged in complex and dynamic tasks seems very plausible and compelling.

Many theories and models suggest that, as expertise is developing, fewer cognitive resources are required to perform a given task. Works of Schneider and Shiffrin [39] showed the distinction between controlled and automatic processing. Anderson [40] proposes the ACT-R (Adaptive Character of Thought-Rational) simulation environment to represent the human learning process. The basic idea is that, as we solve problems, we store solutions in our memory for future use. With ACT-R, Anderson suggests that complex cognition arises from interaction between procedural and declarative memory. Procedural knowledge is represented in units called **production rules** and declarative knowledge is represented in units called **chunks**. The individual units are created by simple encodings of objects in the environment (chunks) or simple encodings of transformations in the environment (production rules). Chunks have different levels of activation to reflect their use: chunks that have been used recently or used very often receive a high activation [41]. Chunks cannot act by themselves; they need production rules for their application. Each production rule has a real-value quantity associated with it called **utility**. Utility is calculated from the estimates of the cost and probability of reaching the goal if that production rule is chosen [41]. Kennedy and Trafton [37] found that ACT-R demonstrates three phases of learning: cognitive problem-solving, recall of previous solutions, and proceduralization of knowledge.

The logic underpinning the production and learning of rules in the ACT-R environment is central to the theory. Such logic is similar to the one supporting the Skills-Rules-Knowledge (SRK) based theory formulated by Rasmussen [18, 19]. Rasmussen's theory describes three discrete levels of cognitive control that a person may use to perform a cognitive task. The level on which a person operates depends on the complexity of the task and their experience and knowledge relevant to the particular situation. The three levels also may be used to characterize different degrees of experience and expertise.

When the situation is entirely new and the person therefore has no rules collected from past experience to apply, information is processed at the knowledge-based level. This level refers to analytical processing and entails the use of conceptual information. A person who is considered a novice in this new situation will begin by assigning meaning to information, and then they will insert all these meanings into an identification frame.

Intermediate learners will possess qualitatively different knowledge and some rules gained from experience. For instance, if a person is familiar with the task but does not have much experience, they will operate at the rule-based level. This level involves the processing of information in terms of recognition of certain meanings and signs. These signs initiate If-Then rules acquired from past experience, linking a particular sign with a specific action.

People operate at the skill-based level when they are greatly experienced with the task; that is, they act in an automatic and subconscious manner toward raw perceptual elements. Finally, these cues will be processed in light of one's goals in working memory, and mental models will often be used to perform simulations and assess action plans [42].

Persons who are novices in a specific situation will act at the knowledge-based level as long as they start storing and using knowledge and rules that allow them to switch to the rules-based level, and eventually to the skills-based level as they become more expert. An expert, depending on the particular features of the task, will be able to switch between levels (for example, if the situation is more uncertain, he may switch to the knowledge-based level).

The Recognition-Primed Decision model (RPD) proposed by Klein [12, 13, 14] suggests such distinctions in the level of decision-making processing based on the level of decision-maker expertise. These levels are: Simple Match (SM), Diagnosis of the Situation (DoS), and Evaluation of the Course of Action (ECoA). The result of the decision-making process for each of these levels is the implementation of the action. However, each includes various steps allowing for adaptation to the complexity and familiarity of the situation. The SM level is activated when the current situation is simple and straightforward; that is, when the crucial elements of the situation, the objectives and the typical course of action to implement are easily recognized and identified [14, 43]. The DoS level is activated by the presence of uncertainty concerning the situation. Diagnosis being an attempt to establish a relationship between an event and causal factors, this process allows the decision-maker to define the situation and find an explanation for it. Because the actions chosen depend on the evaluation of the situation, diagnosis appears to be particularly important in situations involving uncertainty, like C2 settings [43, 44]. The third level, ECoA, is required with more complex situations, and requires the mental simulation of the course of action being considered to evaluate potential difficulties, possible solutions and, consequently, to determine if this action must be implemented or if further evaluation is required to identify a new course of action [43]. Obviously, as someone develops their expertise, situations will become less complex and more familiar. Then, as their expertise develops, the decision-maker should be increasingly able to act at the SM level. Table 4 shows the parallel between the SRK theory and the RPD model.

Table 4: Parallels between the RPD and SRK models.

RPD model	SRK model	Level of expertise	Characteristics
Simple Match	Skill-Based	High	•Familiar and know situations •Automatic actions •Attentional resources minimally required
Diagnosis of the situation	Rule-Based	Middle	•Not frequent but known situations •Controlled actions •« If-Then » rules evaluation
Evaluation of Courses of actions	Knowledge-Based	Low	•Not frequent and unknow situations •Controlled actions •Deep understanding process involving mental simulation

In everyday life we rarely encounter completely new situations. We always have fragments of knowledge that are more or less relevant to new situations. These pieces of knowledge can be used with more or less success in the understanding of the situation process. Expertise cannot be defined as an all-or-nothing concept. Expertise should be seen in a continuum defined by the quantity and quality of domain knowledge. There is a straightforward assumption that experts in a domain possess more relevant knowledge of that domain than a novice. And as someone gains relevant knowledge through learning, the number of unfamiliar situations encountered in that domain should decrease. Figure 7 represents these continuums.

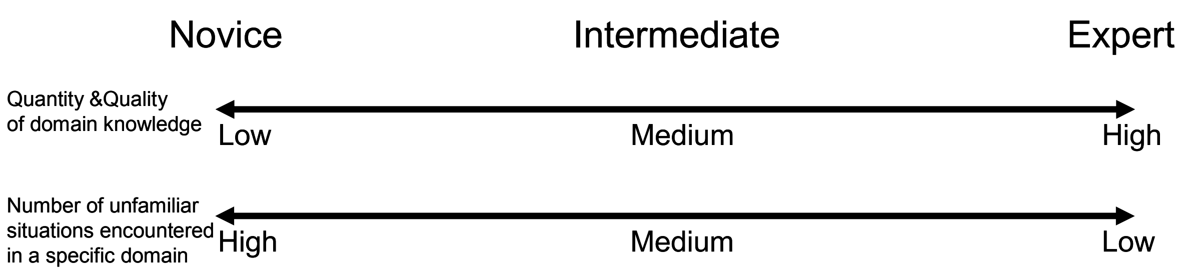

Figure 7: Novice level of information processing in the C-OODA loop.

Obviously, the control components are not based on all-or-nothing criteria either. Quality is a parameter with levels of uncertainty ranging from very low to very high. The same can be said of the importance of the time factor. Based on time pressure, the emphasis could be put either on speed or quality.

In their paper, Breton and Rousseau [8] proposed a model, the C-OODA loop, that made a distinction between the different information-processing levels. They suggested that the distinction specifically involves the control component of the C-OODA loop. In this paper, we go farther with that assumption. We assert that information processing at these different levels follows a similar structure, but that the distinction is made *between the three subcomponents of the control unit* instead. We suggest that the control structure between these units is more simple and straightforward at the expert level than at the novice level.

In order to walk through the model representing the three levels of information processing, we will use a hypothetical situation with fixed parameters. For instance, in order to compare the resulting models together, the time factor will be constant at a minimal level for the three models.

4.1.2 Modelling novice information processing with the C-OODA loop

The modelling of the three different levels of information processing needs to follow some rules and guidelines. As seen in Figure 7, a novice should encounter more unfamiliar and uncertain situations than the intermediate or expert decision-maker. A set of rules governs the uncertainty transfer from one phase to another throughout the decision-making process. Breton and Rousseau [16] identified three properties of uncertainty in the context of the OODA loop: 1) uncertainty arises at every phase of the loop; 2) uncertainty sources vary across the phases; 3) uncertainty builds from one phase to the next. These properties can be used to define some asymmetrical uncertainty rules:

Within each phase:

a. if the output of a low-level process is marked by a high level of uncertainty, then the output of the subsequent high-level process should also be uncertain;

b. <u>but</u>, if the output of a low-level process is marked by a low level of uncertainty, then the output of the subsequent high-level process <u>is not necessarily</u> certain.

Breton and Rousseau state that uncertainty builds from one phase to the next. While that can be true for novice decision-makers, these asymmetrical rules may not necessarily apply universally across all types of decision-makers. For novice decision-makers, between each phase:

a. if the output of a preceding phase is marked by a high level of uncertainty, then the output of the subsequent phases <u>is necessarily</u> uncertain;

b. <u>but</u>, if the output of a preceding phase is marked by a low level of uncertainty, then the output of the subsequent phases <u>is not necessarily</u> certain.

However, a more experienced decision-maker may develop higher level cognitive strategies (i.e. application of if-then rules or mental simulation) that may reverse the application of these asymmetrical rules. Then:

a. if the output of a preceding phase is marked by a high level of uncertainty, then the output of the subsequent phases <u>is not necessarily</u> uncertain if appropriate cognitive strategies are employed.

So, depending on the level of processing, different sets of rules may apply. The modelling of the novice, intermediate and expert level of information processing follows these rules. In the next subsections, each layer included in the C-OODA phase for each level of processing will be detailed.

4.1.2.1 Modelling the Observe phase

In the Breton and Rousseau [8] C-OODA loop, the modelling of the Observe phase is derived partly from the classic feature integration theory proposed by Treisman [10]. This theory suggests that, at a first stage, salient features of stimuli are detected automatically by independent feature modules (i.e., colour, size, distance, etc.). At the second stage, these features are integrated to form a unitary object. While the detection of features in the first stage is cognitively automatic, their integration in the second stage is controlled and requires attentional resources.

Figure 8 presents the bottom part of the C-OODA model. It represents the two layers (low-level and high-level processing) included in the Observe phase. The distinction between the levels of processing does not necessarily occur at the time of detection of features in the environment. Even at the novice level, the features perceived can be sufficiently clear to be recognized. Hence,

Quotient of clearness (Q_{clear}) = should be close to 1 (clear value close to $clear_{expected}$).

Since Q_{clear} should be close enough to 1, the iteration process should also be skipped.

What sets the novice apart from the expert is their lesser degree of domain knowledge. As mentioned previously, the evaluation of current and expected values is subjective, and consequently is totally influenced by the decision-maker knowledge database. In the case of evaluating the clearness of features, one may suppose that any human being has sufficient experience to detect these features with enough confidence.

The influence of knowledge related to the situation (Situation Knowledge) is more important in the next layers of the C-OODA. Consequently, in evaluating the familiarity of the structured objects (Q_{fam}), novice decision-makers face the problem of insufficient knowledge to define what should be the expected state ($fam_{expected}$). As a result, it is almost impossible for them to define the uncertainty quotient (Q_{fam}) and the need for additional iteration (Q_{useful}).

Quotient of familiarity (Q_{fam}) = undefined

Quotient of usefulness (Q_{useful}) = undefined

Then, the decision as to whether or not to execute more iterations (next control unit) will be based more on personality traits such as confidence, perseverance, perfectionism, etc., or metacognitive assessments. As a result, the output of the Observe phase (recognized but undefined objects) is sent as an input to the Orient phase with a specific level of uncertainty.

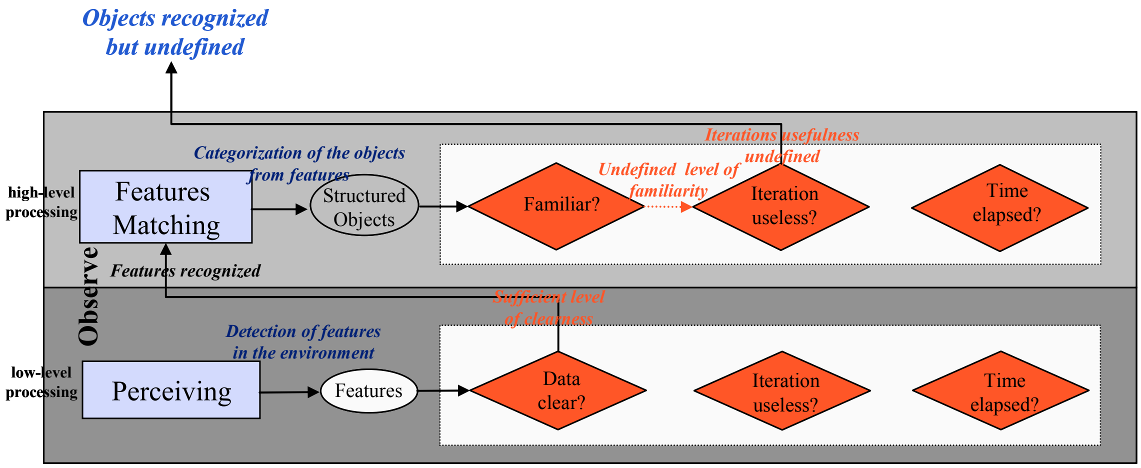

Figure 8: Novice level of information processing: the Observe phase.

4.1.2.2 Modelling the Orient phase

In her theory of situation awareness, Endsley [11] proposes three processes, one being associated with the perception of elements in the environment, and the other two with the comprehension and the projection of the situation in the future. The latter two processes are used in the C-OODA loop to represent the cognitive activities in the Orient phase.

Figure 9 presents the middle part of the C-OODA loop, which includes the layers of the Orient phase. In Figure 9, the recognized but undefined objects (output of the Observe phase) are taken as inputs in the comprehension process. Although it is difficult to define, a high level of uncertainty should characterize these objects. The high level of uncertainty may be due mainly to the absence of known standards. The objective of the comprehension process is to extract causal relationships from these objects. If any if-then rules are stored in long-term memory, those that are most relevant to the domain are activated and used to extract the causal relationships between the objects. The principle of the if-then rules is conceptually similar to those included in the ACT-R theory [35, 36, 37] or those suggested in Rasmussen's SRK classification [18, 19].

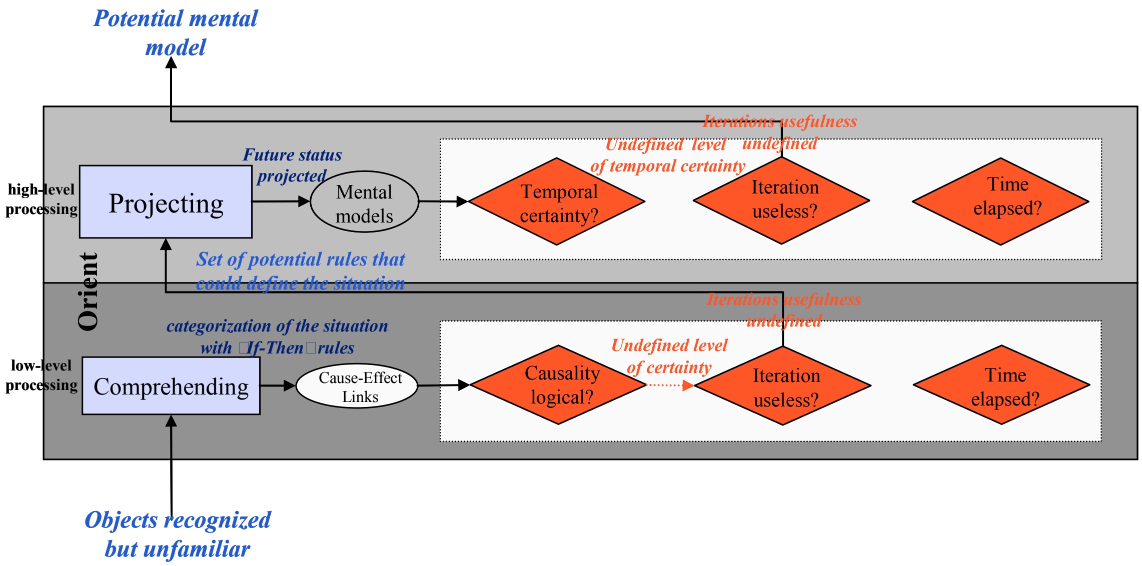

Figure 9: Novice level of information processing: the Orient phase.

At the novice level, lack of relevant domain knowledge may prevent the evaluation of the logic state (log value) and the expected logic value ($log_{expected}$). As a result, it may be difficult for a novice decision-maker to establish causal relationships between objects and establish the uncertainty quotient (Q_{log}). While iterations of the comprehending process should help to correlate objects of greater or lesser familiarity in order to identify causal relationships of greater or lesser certainty, a novice decision-maker may also find it hard to assess the usefulness of further iterations.

Quotient of logic (Q_{log}) = undefined

Quotient of usefulness (Q_{useful}) = undefined

The decision to execute more iterations (next control unit) will be based more on personality traits like confidence, perseverance, perfectionism, etc. Based on the asymmetrical rules governing the uncertainty build-up (p.22), since the outputs (cause-effect links) produced from the first layer of the Orient phase activities should be characterized with a significant level of uncertainty (undefined), the mental model defined from the higher-level processing should also be marked with a significant level of uncertainty. In fact, with the very uncertain and undefined mental model, it may be impossible to project its status in a near future with a certain level of confidence. This projection process relies heavily on the availability of previous experiences. Hence, the execution of the projection process may be challenging for a novice. With such uncertain values (temp value and $temp_{expected}$), it should also be very difficult to evaluate the usefulness of doing more iteration (Q_{useful}).

Quotient of temporal certainty (Q_{temp}) = undefined;

Quotient of Usefulness (Q_{useful})= undefined.

It results in the transfer of an undefined and uncertain mental model that could be the best explanation as possible for the situation. This mental model is sent as an input with its specific level of uncertainty for further processing at the next phase.

4.1.2.3 Modelling the Decide phase

Breton and Rousseau [8] represent the Decide phase with Klein's recognition primed decision model [12, 13, 14]. To make a decision, the decision-maker must recall prototypical actions that seem relevant to the situation and evaluate them from story building or mental simulation strategies. The objective of the recalling phase is to activate prototypical actions that seem plausible to cope with the situation interpreted from the Orient process.

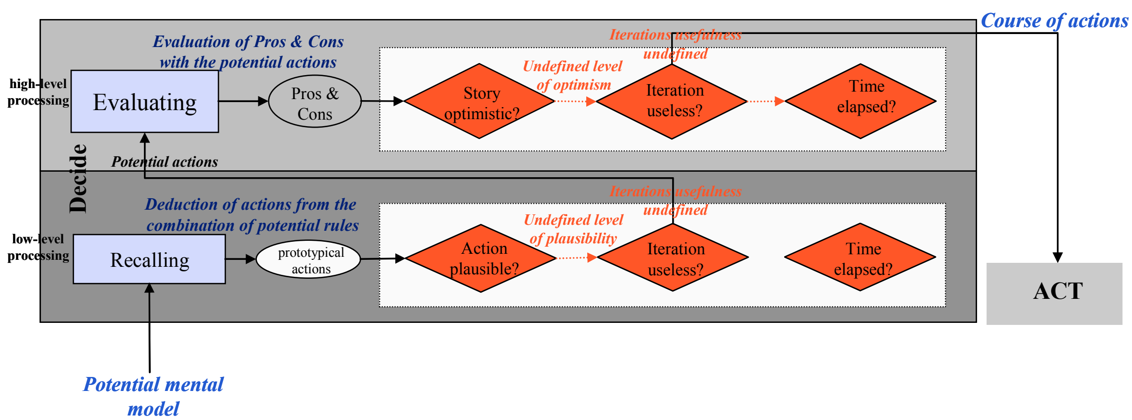

Figure 10: Novice level of information processing: the Decide phase.

Figure 10 represents the top part of the C-OODA, which includes the layers of the Decide phase. In this figure, the potential mental model (output of the Orient phase) is sent as an input to the Decide phase. From this mental model, prototypical actions appropriate to the situation need to be recalled. Obviously, the resulting mental model is characterized by a significant level of uncertainty, so it may be a challenge for a novice decision-maker to recall appropriate actions. Sets of prototypical actions are stored in memory as situation-action couples, which are created on the basis of frequency of exposure to given situations. Novices should then recall, from the best of their knowledge, actions that seem the most plausible for the situation.

Due to a lack of relevant situation knowledge, novice decision-makers should have a hard time recalling actions and evaluating their plausibility (value **plau**) with respect to an expected state ($plau_{expected}$). Based on the difficulty of defining these values, it should also be very difficult to define the usefulness of more iterations (Q_{useful}).

Quotient of plausibility (Q_{plau}) = undefined;

Quotient of usefulness (Q_{useful}) = undefined.

Here again, the decision as to whether or not to execute more iterations (next control unit) would be based more on personality traits like confidence, perseverance, perfectionism, etc.

Given the uncertainty build-up rules (p. 33), problems should also be encountered in the higher level of processing in the phase. It should be very difficult for a novice decision-maker to evaluate the pros and cons of the recalled list of potential actions using story building strategies. Values such as optimism and $optimism_{expected}$ should be difficult to define, so the result should have a high uncertainty level. In addition, the usefulness of more iterations (Q_{useful}) should be difficult to evaluate.

Quotient of optimism ($Q_{optimism}$) = undefined

Quotient of usefulness (Q_{useful}) = undefined

The end result of the Decide phase should be a course of action characterized by a high level of uncertainty.

4.1.2.4 Modelling the Act phase

Breton and Rousseau [8] purposely omitted the Act phase from the C-OODA loop, claiming that it called for more procedural or motor skills. They also suggested that at this very moment, the decision was already made. Then, all cognitive processes involved in the decision-making process could be represented in the first three phases, the fourth being the implementation of the action.

However, from an expertise development and learning standpoint, we suggest that two very important cognitive processes take place during the Act phase. The output of the Decide phase—the selected course of action with its given level of uncertainty—is sent to the Act phase as an input. During action implementation, decision-makers can monitor the execution of the course of action. From this monitoring activity, they should store three different elements of knowledge:

a. the situation and action (situation-action) couples that were analyzed, which should be used to develop If-Then rules;

b. details about the implementation (pros and cons, timing, plausibility of action, feasibility, etc);

c. the final result of the action

These different pieces of knowledge should form the basis for the development of expertise. Then, they should be critical for non-expert decision-makers. As decision-makers become more and more expert, they should possess more and more automatic situation-actions couples and they should be knowledgeable about the implementation of the action, allowing them to rapidly detect unexpected events. Figure 11 presents the C-OODA loop model for the novice information processing level. It illustrates the connections between Figures 8, 9 and 10.

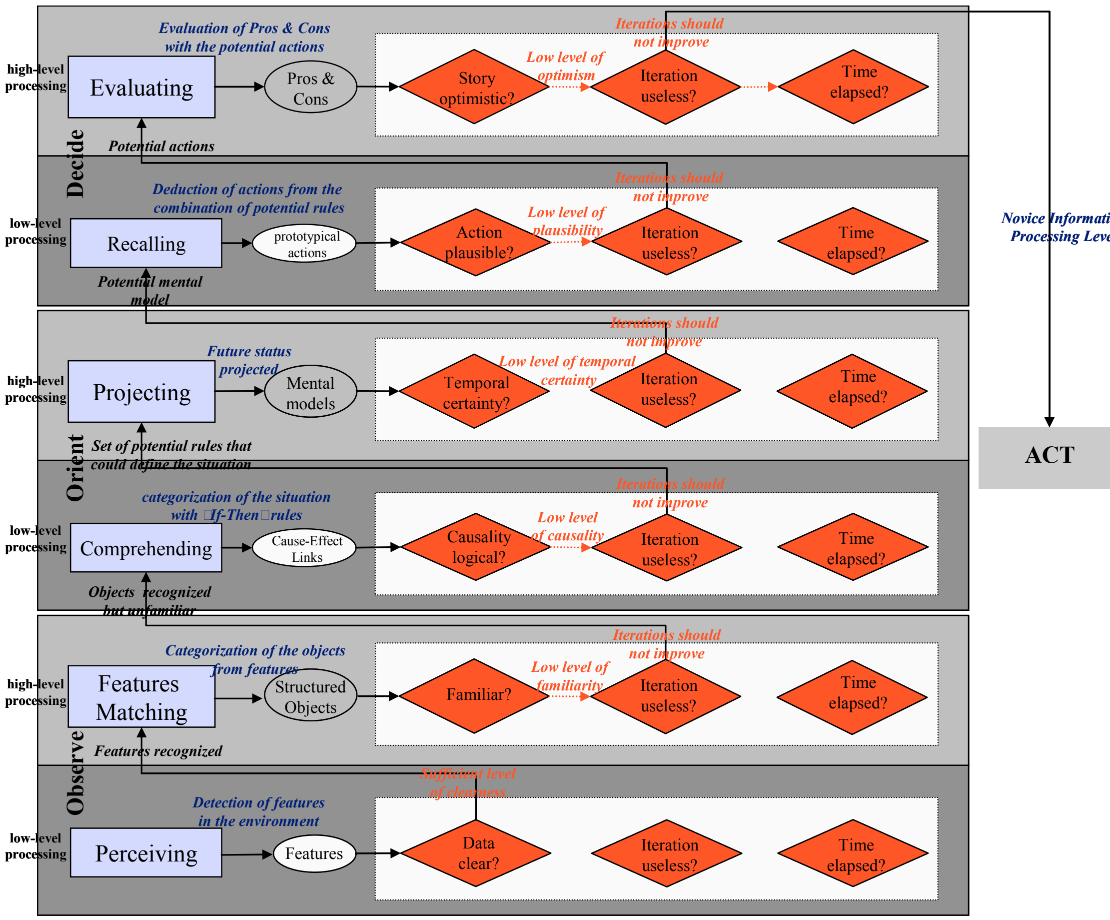

Figure 11: Novice level of information processing in the C-OODA loop.

The following sections describe the intermediate and expert information processing levels. Because the rationale underlying the C-OODA was explained in detail in the previous sections, and for simplicity, we will only provide details about the differences between the three levels of information processing (novice, intermediate, expert).

4.1.3 C-OODA loop representing intermediate information processing

4.1.3.1 Modelling the Observe phase

Figure 12 presents the bottom part of the C-OODA, which includes the layers of the Observe phase at the intermediate level of processing.

As shown in Figures 8 and 12, there is no difference between the novice and intermediate levels of information processing in the Perceiving layer of the Observe phase. In both cases, features can be recognized.

Quotient of clearness (Q_{clear}) = should be close to 1 (clear value close to $clear_{expected}$).

Since Q_{clear} should be close enough to 1, the iteration process should also be skipped.

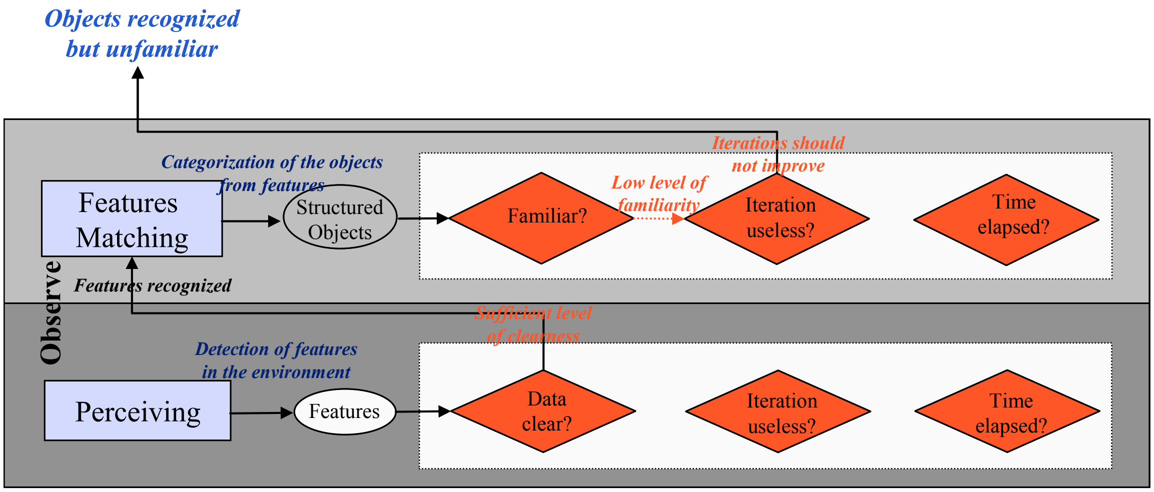

Figure 12: Intermediate level of information processing: the Observe phase.

Visually, the figures may be similar for this process. However, the distinction between the novice and the intermediate level is in the level of familiarity of the structured objects resulting from the Features Matching process. Familiarity is not an all-or-nothing concept. It is difficult to clearly define when an unfamiliar concept becomes familiar. As can be seen in Figure 7 (p. 19), familiarity must be seen on a continuum. The value of the ratio of current state to expected state (defining the value Σ) can vary from less than 1 to equal to 1. Hence, in Figure 12, while the level of familiarity may not reach the threshold (expected state), it may still be higher than the level in Figure 8. In fact, as mentioned previously, the Q_{fam} at the novice level should be hard to evaluate, since novices should find it difficult to accurately evaluate the expected state of familiarity ($fam_{expected}$). It should result in an uncertain and undefined Q_{fam} at the novice level.

Novice level Q_{fam} undefined

However, intermediate decision-makers may have enough situation knowledge to help them to define an expected familiarity state. Consequently, they should be more skilled in evaluating value Q_{fam} because $fam_{expected}$ can be defined. While it can be defined, a significant level of uncertainty should characterize the structured objects. Thus,

Intermediate level $Q_{fam} < 1$

Consequently, at both the novice and intermediate levels, the structured object familiarity is uncertain. However, the level of uncertainty should be higher at the novice level and it should be undefined.

Novice level Q_{fam} < intermediate level Q_{fam}

At the novice level, iteration usefulness (Q_{useful}) is hard to define because the expected state value is unknown. At the intermediate level, the decision-maker may have more situation knowledge to define the $fam_{expected}$ value. Then, the Q_{useful} could be defined. Figure 12 illustrates a situation where iterations are not deemed useful (they do not significantly reduce the level of uncertainty).

Quotient of usefulness (Q_{useful}) close to 0.

This leads to the interruption of the iteration process.

The comparison between the novice and intermediate levels of processing shows the importance of the familiarity parameters in those levels of processing. It is the slight difference in the level of familiarity that could permit execution of the task at the intermediate level of information processing. As in Rasmussen's theory, this assumption makes familiarity the most critical concept for deciding which level an individual is performing at.

4.1.3.2 Modelling the Orient phase

Figure 13 illustrates the middle part of the C-OODA, which includes the layers of the Orient phase at the intermediate level of processing. In this figure, the inputs of the comprehending process (the structured objects) are characterized by a significant level of uncertainty.

Intermediate level $Q_{fam} < 1$

As mentioned before, this level of uncertainty may be lower than that associated with the structured objects of Figure 9. At the novice level of information processing, the structured objects identified from the Observe phase may be totally unfamiliar and/or undefined. At the intermediate level, the lower degree of uncertainty could open the door for an uncertainty reduction procedure such as Data Fusion or the application of cognitive strategies such as If-Then rules, associations, etc. It is possible that two or more unfamiliar and uncertain objects fused together result in a new structured concept with a higher level of certainty. The role of the comprehending process is to extract relatively certain meanings from disparate objects that can be considered unfamiliar when viewed separately. But to do so, the intermediate decision-maker may need minimal knowledge about the situation. More or less relevant If-Then rules can be applied to extract more certain causal relationships. Deductive reasoning is applied to extract those meanings.

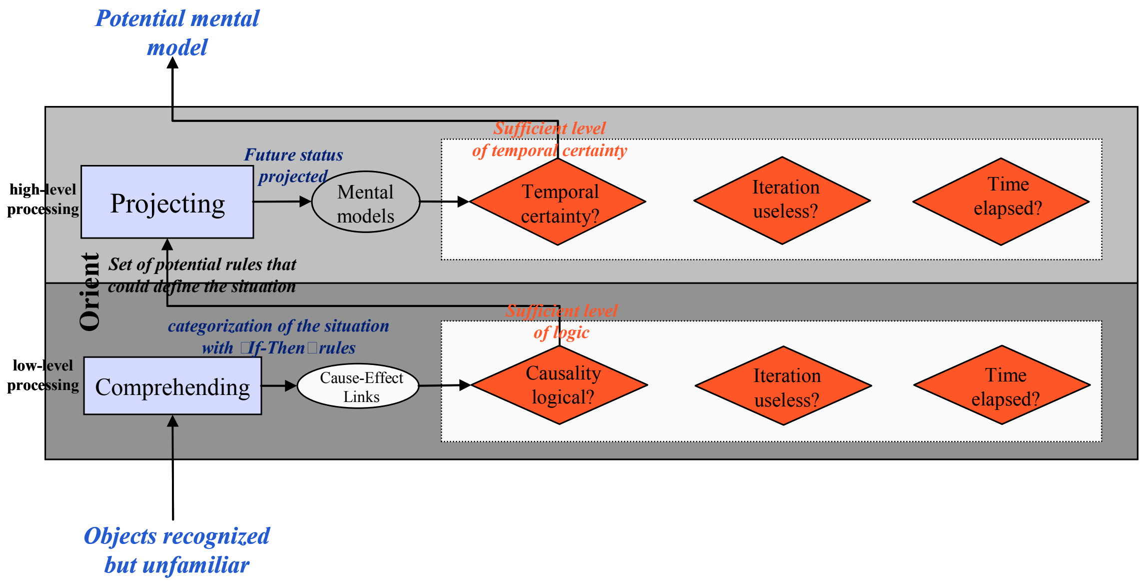

Figure 13: Intermediate level of information processing: the Orient phase.

Figure 13 illustrates a situation where the application of adequate cognitive procedures and strategies to evaluate the logic of cause-effect links leads to an acceptable level of certainty:

Q_{log} close enough to 1

This assumption makes reference to the rules stated on p. 20.

a. if the output of a previous phase is marked by a high level of uncertainty, then the output of the subsequent phases is not necessarily uncertain if appropriate cognitive strategies are employed.

Since Q_{log} is close enough to 1, no iteration is necessary and the cause-effect links are sent as inputs for the next layer (projection).

The next layer is responsible for building a mental model and validating it from a temporal perspective. The inputs considered in this process reach an acceptable level of certainty. As shown in Figure 13, the result of the projection process also reaches an acceptable level:

Q_{temp} is close enough to 1

It should be easier for a decision-maker to project the status of a given situation in the near future when the cause-effect links between objects are considered certain. Note also that Figures 13 and 17 (explained later) are similar. Once a familiar pattern is detected, there is no difference between the intermediate and expert levels of processing at this specific phase.

4.1.3.3 Modelling the Decide phase

Attentional resources are required for the first three phases of the C-OODA loop at the novice level, but at the intermediate level only the Observe phase and the first process of the Orient phase (comprehending) require controlled processing. As soon as a reliable mental model of the situation is deduced, prototypical actions can be recalled and their pros and cons assessed without extensive attentional resources. Then,

Q_{plau} and $Q_{optimism}$ close enough to 1

Figure 14 illustrates a situation where the potential mental model is used as an input for the recalling process. With its relatively high level of reliability (both Q_{log} and Q_{temp} close to 1), this potential mental model leads to the recall of prototypical actions. As the level of certainty increases, this process may become more automatic. Since a certain level of quality is reached, no iteration is necessary, as illustrated in Figure 14. The potential actions are fed into the evaluating process as inputs. Their evaluation may also be automatic and may not require additional iterations. The result is the identification of a course of action characterized by a certain level of confidence.

Figure 14 illustrates the upper part of the C-OODA, which includes the layers of the Decide phase at the intermediate level of processing.

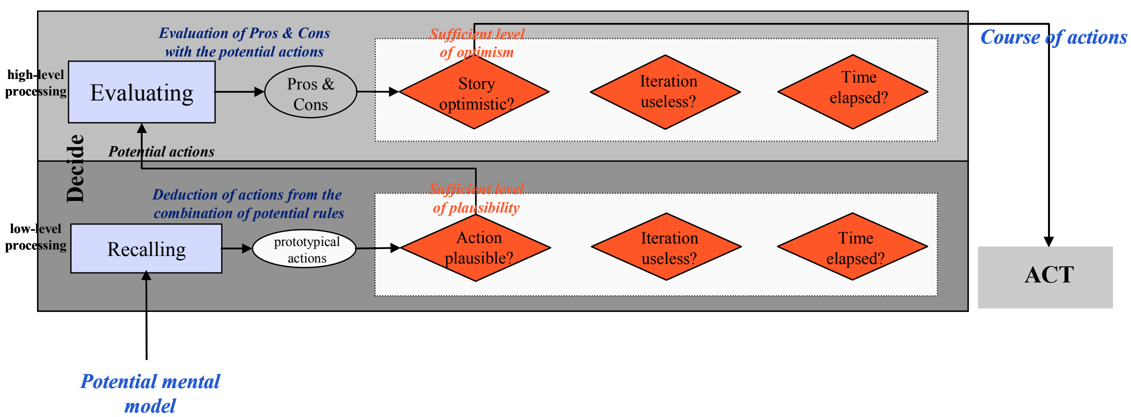

Figure 14: Intermediate level of information processing: the Decide phase.

4.1.3.4 Modelling the Act phase

During implementation of the selected course of action, intermediate decision-makers can monitor the execution of the course of action to:

a. validate the mental model (situation-action couple).

b. detect unexpected events;

c. store the final result of the action.

At the novice level, storing the result of the action increased the pool of knowledge (learning) of the novice decision-maker. At the intermediate level, the same process (storing the result of the action) also expands and validates the intermediate decision-maker's knowledge. While storing new knowledge helps make a novice decision-maker an intermediate decision-maker, validating situation-action couples helps advance intermediate decision-makers to the expert level. Figure 15 presents the overall C-OODA loop model for the intermediate level of processing.

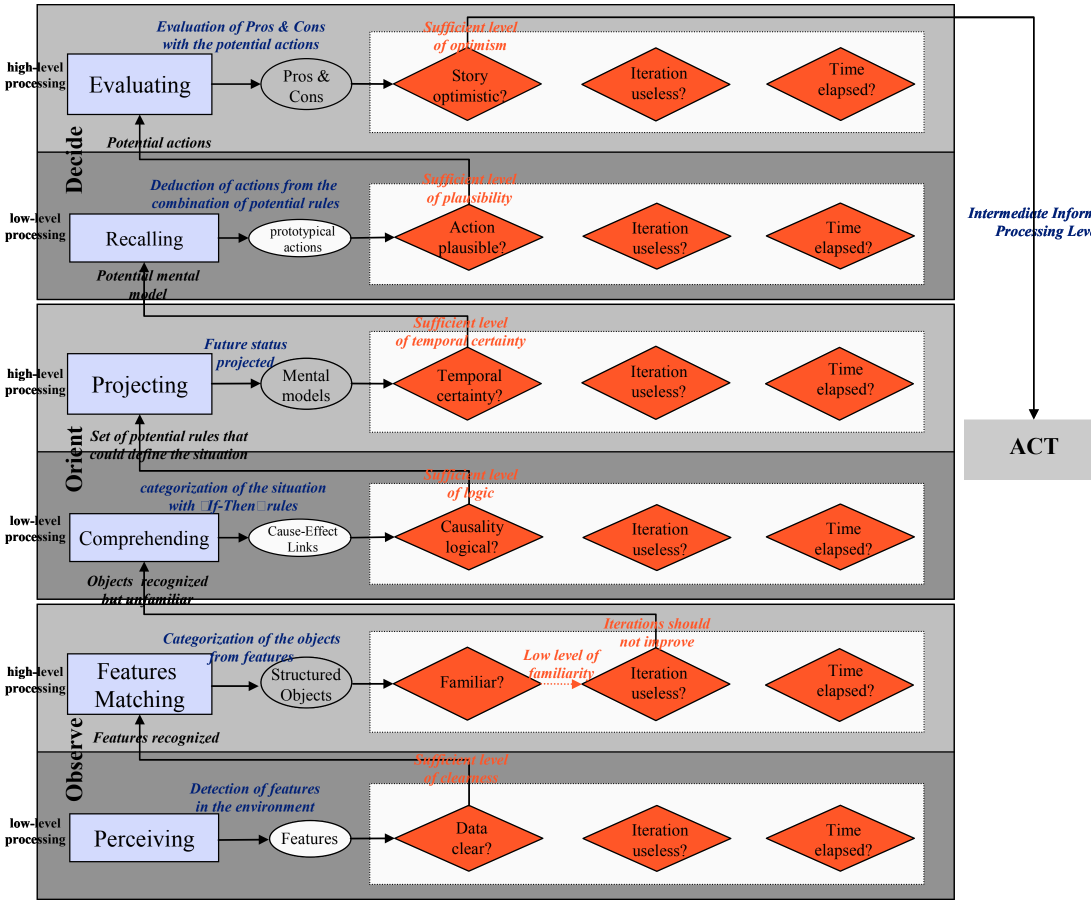

Figure 15: Intermediate level of information processing in the C-OODA loop.

4.1.4 C-OODA loop representing expert level of information processing

4.1.4.1 Modelling the Observe phase

Figure 16 presents the bottom part of the C-OODA, which includes the layers of the Observe phase at the expert level of processing.

While Figures 8 and 12 suggest that the result of the Observe phase is recognized but unfamiliar objects, Figure 16 illustrates a situation where very familiar objects are rapidly recognized. Here again, it concerns the continuity of the familiarity parameter. Experts should encounter more familiar situations than intermediate and novice decision-makers. These situations should be more certain.

This high level of certainty should be related to the fact that the expert decision-maker should possess all the required knowledge to efficiently evaluate the current and expected state for these parameters (clearness and familiarity) and consequently the ratio between them. Figure 16 illustrates the situation where the data are clear and the matching of these features leads to very familiar objects.

Q_{clear} and Q_{fam} close enough to 1

While the perception of the feature may require minimal attentional and cognitive resources, the feature matching process may be automatic as suggested by Treisman's theory of features integration (1988). Obviously, no iterations are necessary in both layers. The end result of the phase is the recognition of familiar objects, which are then transferred as inputs to the next phase.

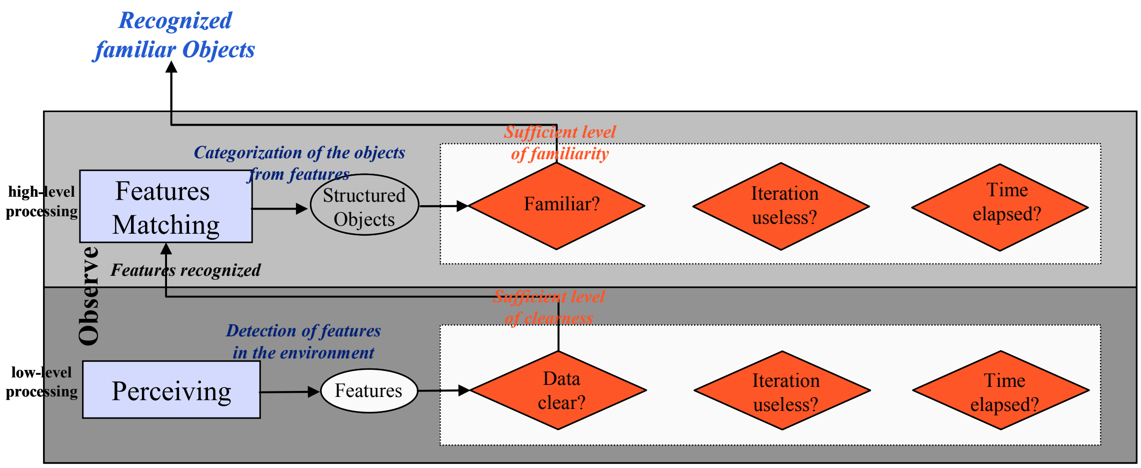

Figure 16: Expert level of information processing: the Observe phase.

4.1.4.2 Modelling the Orient phase

Figure 17 illustrates the middle part of the C-OODA, which includes the layers of the Orient phase at the expert level of processing.

The recognition of very familiar objects leads to the automatic activation of a well-known mental model appropriate for the situation at hand. This automatically activated mental model should already be validated from causality and temporal perspectives. Here again, since the current and expected states are known, the uncertainty quotients are easily established. Figure 17 shows a situation where these quotients are almost equal to 1.

Q_{log} and Q_{temp} close enough to 1

In addition, with highly certain states automatically activated, no iterations are required.

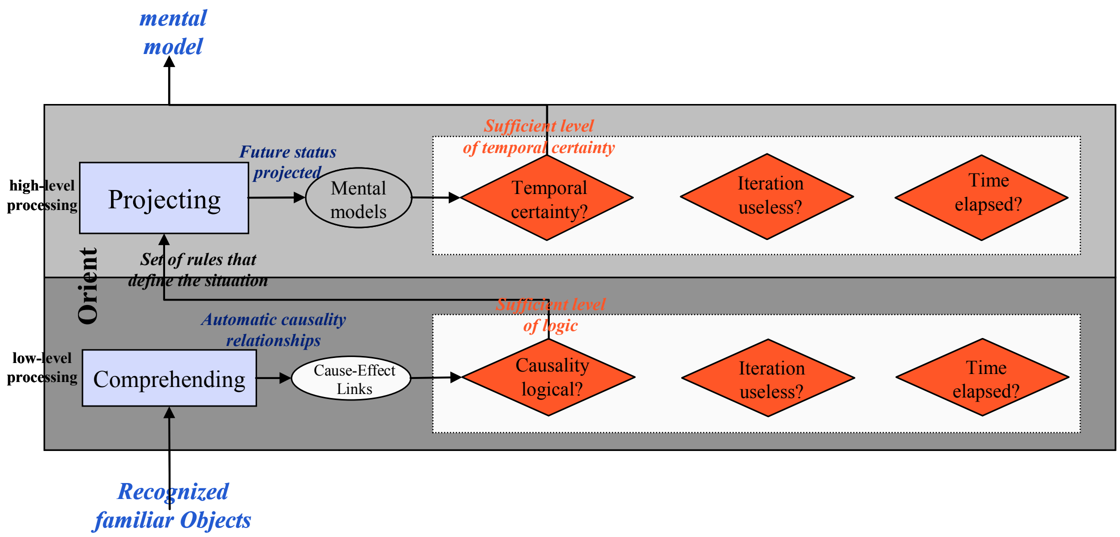

Figure 17: Expert level of information processing: the Orient phase.

The mental model defining the situation is transferred as input to the next phase.

4.1.4.3 Modelling the Decide phase

Figure 18 presents the upper part of the C-OODA, which includes the layers of the Decide phase at the expert level of processing.

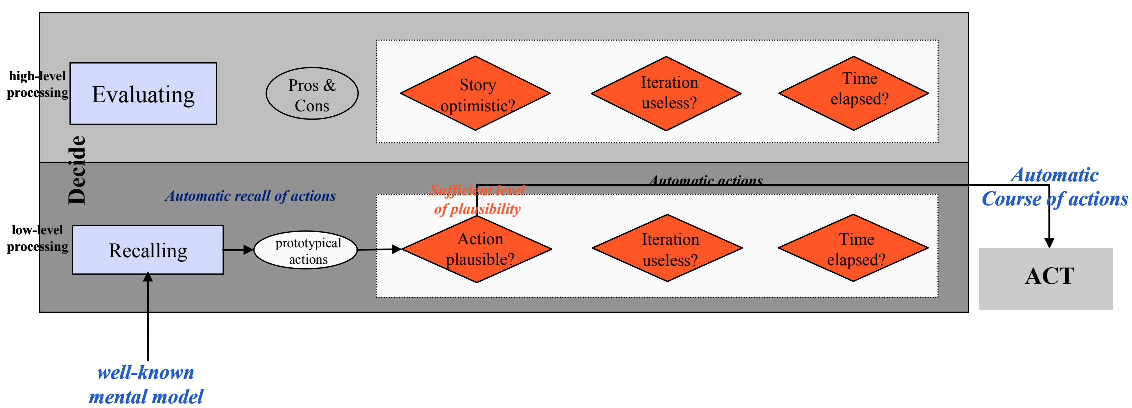

Figure 18: Expert level of information processing: the Decide phase.

There are two distinctions that need to be detailed at this specific phase of the expert level:

1. It may well be possible that the automatically activated mental model includes a well-known and certain course of action;

2. Since it includes a well-known and certain course of action, the last layer of the Decide phase can be skipped (no pros and cons evaluation required).

Hence, at the novice and intermediate levels of information processing, all layers of the C-OODA loop come into play. At the expert level, the last layer of the Decide phase is skipped. The related level of plausibility is very high:

$Q_{plau\ very}$ close or equal to 1

Since these responses are automatic, they do not require an extensive high-level evaluation process such as story building or mental simulation. Note that these latter processes are conscious and require controlled processing.

4.1.4.4 Modelling the Act phase

During implementation of the selected course of action, expert decision-makers can monitor the execution of the course of action to:

a. detect unexpected events;

b. store the final result of the action.

Figure 19 presents the overall C-OODA loop model for the expert level of processing.

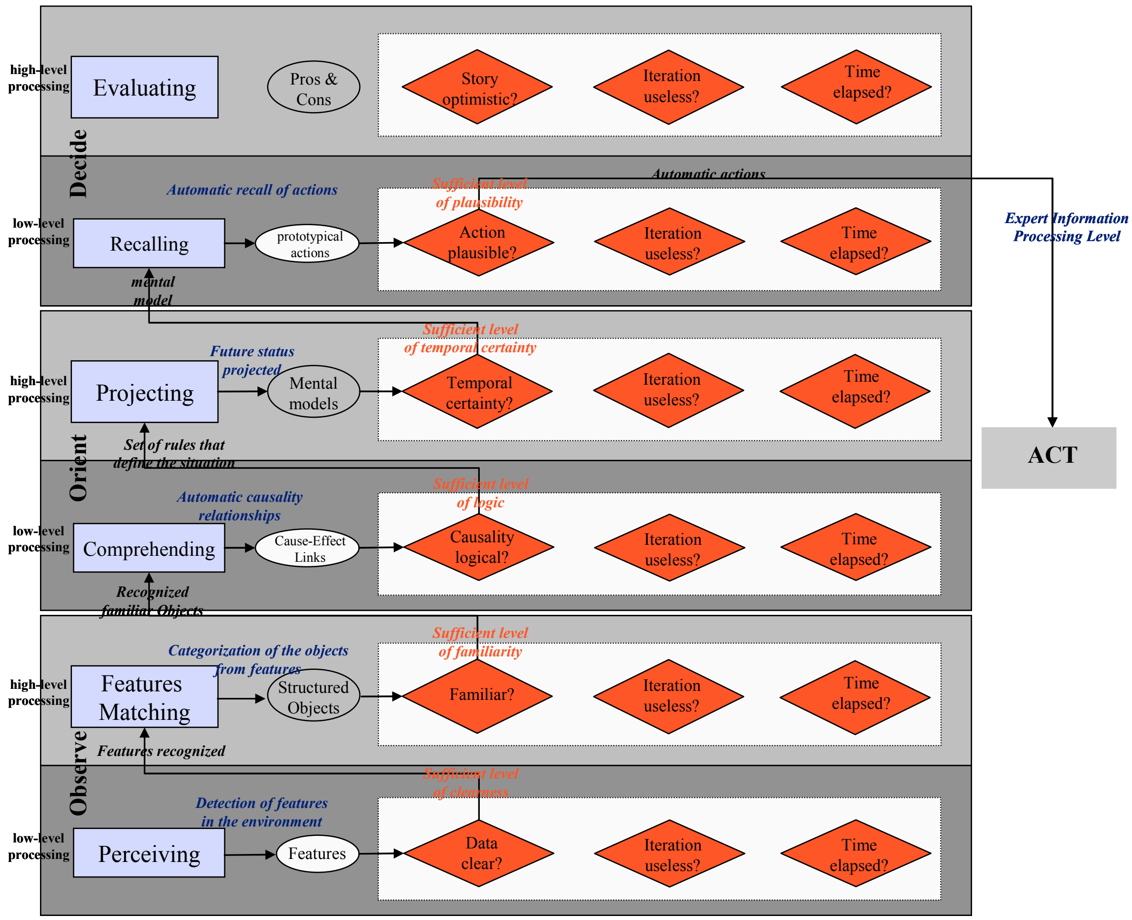

Figure 19: Expert level of information processing in the C-OODA loop.

5 Discussion

According to Rasmussen's classification of Skills-Rules-Knowledge based action control [18, 19], processing at the knowledge-based level requires more time and resources than acting at the other two levels. For instance, acting at the skill-based level, the reaction is almost an automatic reflex triggered by the detection of a very well-known and frequent stimulation. It is effortless and requires a processing time that could be minimized to the detection time of the stimulation and the triggering of procedural processes required to implement the action. This conception is totally compatible with that proposed by Klein [12, 13, 14] in his RPD model of decision-making. In Klein's model, processing the information at the Evaluate Course of Action level should take more time and resources than processing at the Simple Match level. Consequently, experts should act more at the skill-based and Simple Match levels.

In this document, we made the distinction between the different levels of information processing from the criteria-based control units included in the C-OODA loop proposed by Breton and Rousseau [8]. From Figure 11, 15 and 19, we demonstrated that the control structure between the units was simpler and more straightforward at the expert level than at the novice level.

This view is also compatible with those suggested by Rasmussen and Klein. We also support the idea that processing at the novice level should require more time and resources than acting at the expert level. However, we attribute the need for additional processing time and resources to the structure of the control units within the criteria-based control component.

There are other distinctions between the different levels of processing that should be highlighted:

- The impact of the familiarity of the situation: As in the Rasmussen and Klein models, the role of situation familiarity is crucial in our conception. In our model, we relate the familiarity level to the capacity of the decision-maker to assess the uncertainty of the situation. We not only assert that highly familiar situations are relatively certain, we also suggest that the decision-maker is can define the level of certainty of the situation and act accordingly.
- The importance of the knowledge database: Familiarity is dependent on a sufficient knowledge database. The content of the knowledge database should support the subjective evaluation of the current situation (current value), what the situation should be (expected value), and the discrepancy between these two values (determining the need for more processing). We suggest that lack of a sufficient knowledge database should make it difficult to determine these values. The result would be undefined parameters characterized by high uncertainty.
- The role of the Act phase according to the level of processing: Breton and Rousseau [8] kept the level of modelling of the phase minimal. While here we do not provide further details on the cognitive and procedural resources supporting this phase, we identify a specific role for the Act phase in the decision-making process. For the novice decision-maker, the Act phase is very important. During that phase, the novice will identify and store in his/her knowledge database situation-action couples and details about the action implementation for future reference (when this situation occurs anew). In that sense, the Act phase is seen as a period in which the novice decision-maker will observe the result of his/her decision-making

process in order to gain experience for future processes. This information will constitute the content of the knowledge database. For the intermediate decision-maker, the Act phase is used to validate more defined situation-action couples and to monitor for unexpected events. With information processing at the expert level, during the Act phase the expert will only monitor for unexpected or abnormal events.

- Automatic/controlled processing: In this document, we assert that the structure of the control component of the expert decision-maker is simpler and more straightforward. In other words, we could also say that the structure simply requires less effort than those characterizing intermediate and novice processing. According to Figure 11, at the novice level, all phases require controlled processing. Figure 15 shows the intermediate level of processing. Based on this figure, only the Observe and the first level of the Orient phases may require controlled processing. Finally, based on Figure 19 (expert level of processing), upon detection of a very familiar situation, all processes may operate in automatic mode.

5.1 Identifying potential design requirements

The C-OODA model is based on the M-OODA framework [9]. The M-OODA framework (see Figure 20) led to the development of other OODA models intended to address different aspects of C2. For instance, Breton and Rousseau [16, 45] presented a version of the M-OODA loop that addressed the team dimension (T-OODA loop). In a cognitive version of the M-OODA loop dubbed the C-OODA loop, Breton and Rousseau [8] increased the level of cognitive granularity of the M-OODA loop to better support the design of decision aids adapted to C2 environments. Together, the M-OODA, C-OODA and T-OODA models offer a framework to illustrate the different aspects of C2.

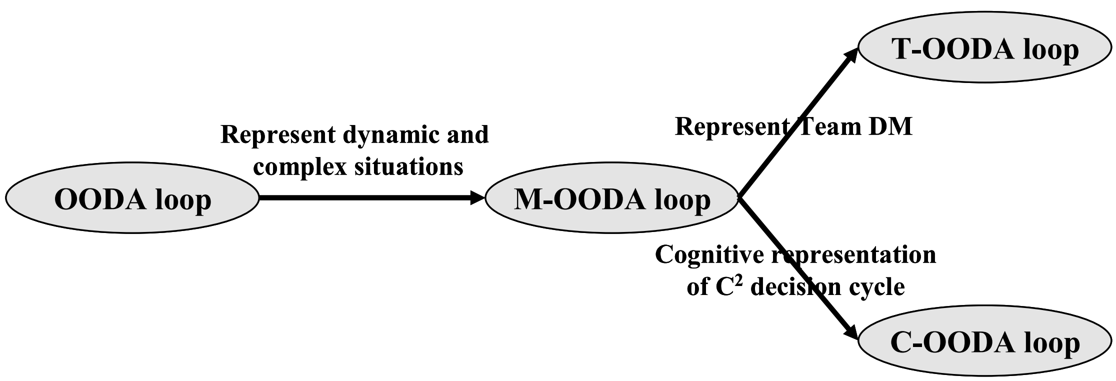

Figure 20: The M-OODA framework and related C2 models.

The objective of this modelling effort is to facilitate understanding of a given task execution under specific conditions. As mentioned by Breton and Rousseau [8], the existing version of the OODA loop [1] does not offer a sufficient level of cognitive granularity to be useful in the development of C2 support systems.

This paper is an extension of Breton and Rousseau's work [8] in that it provides more details on the cognitive processes included in the C-OODA, specifically the role and contents of the control criteria-based units. From the C-OODA proposed by Breton and Rousseau [8] and this paper, generic design requirements can be identified. The design requirements identification must be based on the cognitive processes included in each C-OODA phase, their objectives, the nature of the process and the data considered in their execution.

Actually, two different levels of cognitive processes come into play in the C-OODA at different levels of processing. First, there are cognition processes supporting the execution of the OODA phases, particularly the execution of the layers. Second, there are the cognitive processes that support the cognitive strategies used to reduce the uncertainty level at each layer. The next subsections present a list of potential problems for a human decision-maker executing the C2 decision cycle. Obviously, the problems stated concern more the novice and intermediate decision-makers. In this document, it was not our intent to identify specific technological solutions. Instead, we provide an identification of problems and design requirements for these two levels of cognitive processes.

5.1.1 Supporting execution of C-OODA phases

5.1.1.1 Supporting the Observe phase

Processes: Perceiving and Features Matching

Objectives: Extracting meaningful data from the environment. Meaningfulness is evaluated from an expected state perspective (also influenced by the commander intent).

Data considered: Inputs from the environment

<u>Potential problems in the execution of this phase</u>

1. To detect clear data: Perceptual problems

Rationale: The availability of meaningful data and their presentation to a human decision-maker through an interface is critical. Based on Treisman's theory [10], the detection of data from the environment is relatively rapid and most of the time automatic. However, the Features Matching process may call for controlled processing, particularly in the case of unfamiliar features. Clearness of data is a critical factor in the detection of meaningful data. Novices may have a problem detecting appropriate information.

Potential solutions: Support is required to provide detectable data from the environment. Support should seek to increase the decision-maker's level of confidence in the data.

2. To evaluate object familiarity: Lack of domain knowledge (lack of standards)

Rationale: The evaluation of object familiarity means that objects are compared with standards. These standards are derived from appropriate training, previous experiences, etc., and are stored in the decision-maker's long-term memory. The novice's lack of experience and domain knowledge means that they should find it hard to define standards (expected state). Even though intermediate decision-makers have some domain knowledge, they may also encounter problems defining object familiarity. Note that this evaluation process is subjective and may suffer from a lack of expertise.

Potential solutions: Support is required to help novice decision-makers to define what should be an ideal state and to help intermediate decision-makers to assess the familiarity of objects. Support could be in the form of appropriate training or knowledge databases.

5.1.1.2 Supporting the Orient phase

Processes: Comprehending and Projecting

Objectives: Making sense (logical and temporally valid) out of the data extracted from the environment. Logic and temporal validity are determined in reference to an expected state (also influenced by the commander intent).

Data considered: Structured objects built from the Observe phase

Potential problems in the execution of this phase

1. **Making sense of a given set of disparate objects: Lack of domain knowledge (lack of standards) and insufficient short-term memory**

Rationale: Making sense out of a situation requires relevant domain knowledge. Here again, novices may lack relevant domain knowledge. Also, establishing relationships between disparate objects demands the manipulation of the concepts in short-term memory, which has limited capacity. Intermediate decision-makers may be more successful but still have to handle a high workload in short-term memory.

Potential solutions: Support is required to provide domain knowledge databases. It should also seek to reduce the workload in short-term memory related to complex situations (including several objects). Automatic recognition systems (like case-based reasoning systems) could be considered.

2. **Validating relationships between objects from a temporal perspective: Lack of domain knowledge (lack of standards) and insufficient short-term memory**

Rationale: Validating relationships between objects from a temporal perspective means that predictions must be made over the potential evolution of the object status. The projection task creates a high workload in the short-term memory. This task may call for higher-level cognitive tasks, such as mental simulation. As the complexity of the situation and the number of elements involved increase, the workload also increases. Task execution may be very difficult for a novice decision-maker with the high uncertainty that characterizes the objects and their relationships.

Potential solutions: Technological devices for simulating the situation over a given period of time (with a level of confidence provided) would be helpful. Such devices would also aid intermediate decision-makers in validating their assumptions.

5.1.1.3 Supporting the Decide Phase

Processes: Recalling and Evaluating

Objectives: Recalling appropriate courses of action based on situation understanding. Evaluating the pros and cons of the selected course of action.

Data considered: Mental model built from the Orient phase.

Potential problems in the execution of this phase

1. **Recalling appropriate courses of action: With an undefined and uncertain mental model**

Rationale: When the situation is undefined and characterized by very high uncertainty, determining an appropriate response pattern may be very difficult. While automatic response patterns are often triggered in very familiar situations, most undefined and uncertain situations do not suggest the appropriate response pattern. A prerequisite for recalling an appropriate course of action for a given situation is to have the course of action in a database (in long-term memory). Another prerequisite for a good recall process is to base the recalling activities over relatively certain mental models of the situation. Hence, novice decision-makers may encounter very significant problems recalling an appropriate course of action (often unavailable in long-term memory) from undefined and uncertain mental models. The root of this problem is in the previous C-OODA phase. In fact, the most important problem is an undefined and uncertain mental model. As a result, supporting the previous phase execution (comprehending and projecting) with appropriate technological devices (i.e., case-based reasoning systems or systems based on lessons learned) could be a better strategy to solve the problem of recalling appropriate courses of action.

2. **Evaluating courses of action: Lack of domain knowledge and insufficient short-term memory**

Rationale: If a response (action) is absolutely necessary, novice decision-makers will try to the best of their knowledge to find the best alternative. At the expert level of information processing, this process is skipped. The underlying rationale is that the course of action is well known and approved and does not need further evaluation. At the novice and intermediate levels, this process is very important. It can be seen as the last gate before implementing action. For the novice decision-maker, this task should be very difficult to execute. The lack of domain knowledge and the presence of undefined and uncertain mental models make the task almost impossible to perform. In addition, the manipulation of very complex, uncertain and disparate pieces of information may create a considerable workload in the short-term memory. At the intermediate level, this task may be more easily performed. Intermediate decision-makers may increase the situation certainty by combining different relevant sources of information. The result may be a more certain mental model where a potential course of action is more obvious. The evaluation of the potential course of action (pros and cons) through story building or mental situation may be more fruitful. However, it might require very substantial attentional and memory resources. Consequently, technological tools should be developed to support these cognitive strategies (for instance, a critiquing system).

5.1.1.4 Supporting the Act Phase

Breton and Rousseau [8] did not increase the level of cognitive granularity of the Act phase, arguing that this specific phase calls for different resources (i.e., procedural resources). They also suggested that the decision had already been made at this specific phase, and that the Act phase is only the implementation of the action.

While we did not offer more details on the cognitive processes supporting the Act phase of the C-OODA, we have identified some cognitive activities that are noteworthy for the identification of design requirements. During the Act phase, the following activities are usually performed:

1. validation of the appropriateness of the selected course of action (monitoring);
2. detection of anomalies and unexpected events;
3. storage of three specific information elements:
    a. situation-action couples (rules learning)
    b. details about the implementation (supervising)
    c. final results.

These activities can transform novices into intermediate and expert decision-makers. These activities are responsible of the development of expertise and learning. However, executing these functions demands considerable cognitive resources (attention and memory). Accordingly, they should be considered in the development of training programs and support systems.

5.1.2 Supporting the transition between C-OODA phases

The output of the Observe phase is a set of structured objects with a specific level of uncertainty. The output of the Orient phase is a given mental model with a specific level of uncertainty. Finally, the output of the Decide phase is a potential course of action with a specific level of uncertainty. The different levels of uncertainty associated with these phase outputs seems to be the factor that distinguishes the novice from the intermediate and the intermediate from the expert. For novice decision-makers, the levels of uncertainty characterizing these outputs are considerably higher than those encountered by intermediate and expert decision-makers. For experts, the level of uncertainty is manageable. Another important aspect is that uncertainty is carried over from phase to phase. Some rules have been stated to govern the uncertainty build-up between phases.

For a novice decision-maker, between each phase:

a. if the output of a preceding phase is marked by a high level of uncertainty, then the output of the subsequent phases <u>is necessarily</u> uncertain;

b. <u>but</u>, if the output of a preceding phase is marked by a low level of uncertainty, then the output of the subsequent phases <u>is not necessarily</u> certain.

However, a more experienced decision-maker may develop higher-level cognitive strategies (i.e., application of If-Then rules or mental simulation) that may reverse the application of these asymmetrical rules. Then:

a. if the output of a preceding phase is marked by a high level of uncertainty, then the output of the subsequent phases is not necessarily uncertain if appropriate cognitive strategies are employed.

Some cognitive strategies are used by more experienced decision-makers (specifically intermediates) to considerably reduce the uncertainty level of a given output produced by a preceding phase.

Between the Observe and Orient phases: Strategies such as the application of If-Then rules (deductive reasoning) are used to extract meanings among disparate objects. It is precisely that capacity that distinguishes the novice decision-maker from the intermediate. Intermediate decision-makers will correlate objects in order to increase their level of certainty and their level of confidence regarding the objects (similar to data fusion). Due to automatic processing, expert decision-makers do not need such high-level and resource-intensive processing. The correlation of different objects is a deductive reasoning task. Deductive reasoning is a logical technique in which particular conclusions are drawn from general principles [46].

Johnson-Laird [47] has identified four types of principles: 1) relational inferences (i.e. greater than); 2) propositional inferences (i.e. If-Then); 3) syllogisms based on pairs of premises, each containing a single qualifier; and 4) multiplying quantified inferences based on premises containing more than one qualifier. Inductive reasoning can also be used in the correlation of the structured objects produced from the Observe phase execution. In inductive reasoning, conclusions are usually expressed implicitly or explicitly in terms of probability statements [47]. Both deductive and inductive reasoning require significant attentional and memory resources. While a computer may manipulate enormous quantities of information (statements), human decision-makers have limited memory capacity. Inductive and deductive reasoning are also prone to human error (highly based on subjective judgment). Consequently, it should be supported with appropriate technological tools (i.e. case-based reasoning systems, lessons learned systems or computational models).

Between the Orient and Decide phases: The output of the Orient phase is a given mental model with a specific level of uncertainty. For expert decision-makers, the level of uncertainty is low enough to obviate the need for higher-level cognitive strategies such as story building and mental simulation. Novices will often encounter high-level uncertainty states, making the use of such strategies very difficult. These kinds of strategies are probably more appropriate for intermediate decision-makers, who possess enough domain knowledge and are faced with more manageable uncertainty levels. Story building and mental simulation can also refer to imagery (although not exclusively reserved for visual imagery). Consequently, these activities demand very large memory and attentional resources. They are prone to human error and should be supported with technological tools to reduce the memory workload.

6 Conclusion

Breton and Rousseau [9] proposed the M-OODA model, a descriptive model of decision-making in C2 based on the classic representation of the OODA loop. It provides a means to model decision-making at the required level of complexity while maintaining the coherence of the model. The M-OODA framework (see Figure 20, p. 42) led to the development of other OODA models that address different aspects of C2. For instance, Breton and Rousseau [45] presented a version of the M-OODA loop that addressed the team dimension (T-OODA loop). Breton and Rousseau [8], in a cognitive version of the M-OODA loop dubbed the C-OODA loop, increased the level of cognitive granularity of the M-OODA loop to better support the design of decision aids adapted to C2 environments.

The fact that all these models addressing different aspects of C2 trace their roots to the classic version of the OODA loop can facilitate acceptance of the models by the military community. The whole set of these different OODA loops provides a general framework to 1) represent dynamic and complex situations (M-OODA), 2) represent team decision-making (T-OODA), and 3) provide a cognitive representation of the C2 decision cycle. Being derived from the OODA loop and based on the same architecture, all the models are compatible. They exhibit the advantages of the OODA loop while addressing specific OODA loop limitations.

While Breton and Rousseau [8] considerably enhanced the level of cognitive granularity in their version of the C-OODA loop, details were still lacking in some areas. For instance, few details were provided on the control criteria-based units. We have addressed this problem here. We provided detailed descriptions of these three units. In addition, we defined parameters related to the uncertainty of the state. Uncertainty quotients representing the ratio between the current state (subjective judgment representing the state of mind) and the expected state are provided for each state produced from the different processes of the C-OODA. It also allows the identification of rules governing the interaction between these three units based on a speed/accuracy trade-off.

This formalism could lead to the development of a computational model of the C-OODA loop. However, these efforts need to be coupled with others that provide formalism for the other components of the C-OODA. Actually, formalism only addresses the control components. Grant [7] proposed an operational-view architecture that unifies planning and control based on the OODA loop. He proposed a reconstructed version of the OODA loop including additional components such as planning and sense-making, formalized using structured analysis and design technique (SADT). This formalism can be seen as a step forward toward the development of a computational model of the C-OODA loop. It would then provide valuable information on the human information processing activities in complex environments such as C2. It could help bridge the gap between models proposed from a human factor perspective and solutions that are technology-driven.

The detailed description of these three units allowed us to model three levels of information processing (novice, intermediate and expert). It allowed us to establish comparisons between the levels in terms of controlled/automatic processing and processing time according to the C-OODA phase for each level. Finally, it also gave us the opportunity to identify potential cognitive strategies that can be used by decision-makers to overcome problems such as high levels of state uncertainty. From these analyses we were able to identify a list of cognitive processes and strategies that should be technologically supported in order to help novice and intermediate decision-makers to execute the task with an acceptable level of performance and to allow them to reach the expert level quicker and easier.

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List of acronyms

ACT-R	Adaptive Character of Thought - Rational
C2	Command and Control
COCOM-T	Contextual Control Model - Temporal
C-OODA	Cognitive Observe-Orient-Decide-Act
DND	Department of National Defence
DoS	Diagnosis of Situation
ECoA	Evaluate Course of Action
M-OODA	Modular Observe-Orient-Decide-Act
NDP	Navy Doctrine Program
OODA	Observe-Orient-Decide-Act
PCT	Perceptual Control Theory
RPD	Recognition Primed Decision
SA	Situation Awareness
SM	Simple Match
SRK	Skill-Rule-Knowledge
T-OODA	Team Observe-Orient-Decide-Act

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The modeling of three levels of cognitive controls with the Cognitive-OODA loop framework

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Designing decision aids suitable for C2 environments requires models with a sufficient level of cognitive granularity. With its low cognitive granularity level, the existing OODA loop commonly used to represent the C2 decision cycle cannot sufficiently support the design of decision aids. In an effort to increase its level of cognitive granularity, Breton and Rousseau [8] proposed the C-OODA loop. However, this model offered few details on the control criteria-based components that govern the quality of the state produced from each cognitive process and the information transfer between these processes.

The objective of this document is to address this problem by providing more details on these units and their parameters. From this, the modeling of different levels of information processing is done. This modeling effort provided the opportunity to identify potential cognitive strategies that can be used by decision-makers to overcome problems such as a high level of state uncertainty. These analyses yielded a list of cognitive processes and strategies that should be technologically supported in order to help novice and intermediate decision-makers to execute their tasks with an acceptable level of performance and to allow them to attain the expert level sooner and more easily.

Le développement de systèmes d'aide à la décision pour les environnements de C2 doit se baser sur des modèles offrant une granularité cognitive adéquate. Avec son bas niveau de granularité cognitive, la boucle OODA communément utilisé pour représenter le cycle décisionnel en C2 ne peut influencer suffisamment le design de système d'aide. Dans un effort pour contrer ce problème, Breton & Rousseau [8] ont proposé la boucle C-OODA. Cependant, ce modèle offre peu de détails sur les composantes de contrôle qui gouvernent la qualité de l'état produit par chacun des processus cognitifs et le transfert d'information entre ces processus.

L'objectif de ce document est d'adresser ce problème en fournissant davantage de détails concernant ces unités et leurs paramètres. La modélisation de trois niveaux de traitement d'information permet l'identification de stratégies cognitives pouvant être utilisées afin de diminuer l'impact de hauts niveaux d'incertitude dans la situation. À partir de ces analyses, une liste de processus cognitifs et de stratégies pouvant être supportés par la technologie de façon à aider les novices et intermédiaires à exécuter la tâche avec un niveau acceptable de performance et leur permettre d'atteindre un statut d'expert plus rapidement a été élaborée.

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Cognitive control; information processing; expertise development; OODA loop; decision-making; modeling; situation awareness; temporal control; knowledge database; design requirements

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