The Cognitive Costs and Benefits of Automation

Dr Richard Breton
DRDC-RDDC Valcartier
2459 Pie-XI Blvd North
Val-Bélair, Québec G3J 1X5
CANADA
Tel.: 418-844-4000 (ext.:4753)
Fax: 418-844-4538
Richard.Breton@drdc-rddc.gc.ca

Dr Éloi Bossé
DRDC-RDDC Valcartier
2459 Pie-XI Blvd North
Val-Bélair, Québec G3J 1X5
CANADA
Tel.: 418-844-4000 (ext.:4478)
Fax: 418-844-4538
eloi.bosse@drdc.rddc.gc.ca

SUMMARY

In complex environments like Command and Control (C^2) where human errors may have tragic consequences, intelligent automated systems are essential to execute complex tasks such as situation assessment and decision-making. However, because C^2 environments are also dynamic, it can be difficult for the machine to adapt to the changing and unstable conditions of the environments. Human capacity of adaptation is then required. Because the human cannot be completely replaced or removed from the execution of these tasks, the interaction and coordination between the human and the automated systems become crucial. This paper discusses the cognitive costs and benefits related to the automation within the execution of all processes that lead to the course of action selection. Among the benefits identified, the human workload and the demand of attentional resources can be significantly reduced. A major cognitive cost of automation can be attributed to the shifting role of the human in the execution of a task. With automated systems, the role of human is to supervise their functioning. The more passive role for the human may prevent him to build an appropriate mental model of the situation that is essential for the recovery of system failures.

INTRODUCTION

The Benefits of the Automation

In complex environments like Command and Control (C^2) where human errors may have tragic consequences, intelligent automated systems are essential. With the increasing number of information to be processed, the human information processing capability becomes rapidly overloaded. In addition with these numerous sources of information, the tempo and the complexity of the environment is also increased with the development of the technology. High stake environments such as C^2 produce a considerable amount of stress that affects the human performance. The performance is also affected by the level of fatigue felt by the human. All these factors may produce variability in the performance contribute for human errors and the miss achievement of the task.

The automation can be seen as a potential solution to these problems. Several cognitive benefits can be attributed to the automation. Among them, are:

- The reduction of the operator's workload.

Paper presented at the RTO HFM Symposium on "The Role of Humans in Intelligent and Automated Systems", held in Warsaw, Poland, 7-9 October 2002, and published in RTO-MP-088.

Report Documentation Page

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
00 OCT 2003	**N/A**	**-**

4. TITLE AND SUBTITLE	
The Cognitive Costs and Benefits of Automation	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **DRDC-RDDC Valcartier 2459 Pie-XI Blvd North Val-Bélair, Québec G3J 1X5 CANADA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001577., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- With automated systems, operator's attentional resources can be allocated to other tasks executed concurrently.
- The reduction of the stress factor induced by the stakes of the situation.
- The reduction of the fatigue factor.
- Automated systems provide a certain level of stability in the execution of a task.
- Automated systems can significantly reduce the occurrence of human errors.

In addition to these cognitive benefits, many other benefits related to data monitoring and analysis capabilities can be attributed to automation. On one hand, automated systems can support deductive reasoning capabilities. They can easily consider an impressive number of alternatives simultaneously. However, these systems can hardly make inductive reasoning which require some creativity. On the other hand, humans can hardly deal with several hypotheses at the same time, but have the capacity to make inductive reasoning. Consequently, the human cannot be removed from the picture and an adequate interaction between the automated systems and the human must be established. According to Mosier and Skitka (1996), the combination of human decision maker and automated decision aid should, ideally, result in a high-performing team, maximizing the advantages of additional cognitive and observational power in the decision-making process.

The Interaction between the Human and the Automated or Support Systems

As mentioned above, even with highly automated systems, the human has still a significant role to play in the execution of the task. However, his level of implication is obviously modified according to the type of systems (support or automated system) available for the execution of the task. Figure 1 presents three basic situations that describe the relationship between the task, the human and the tool (automated or support system). The triad presented in this figure is based on the TRIAD framework developed by Breton, Rousseau and Price (2001). This structural model is used to analyze the relationships between the elements defining the TRIAD and to clarify the mandate of every specialist involved in the design process of a particular decision support system.

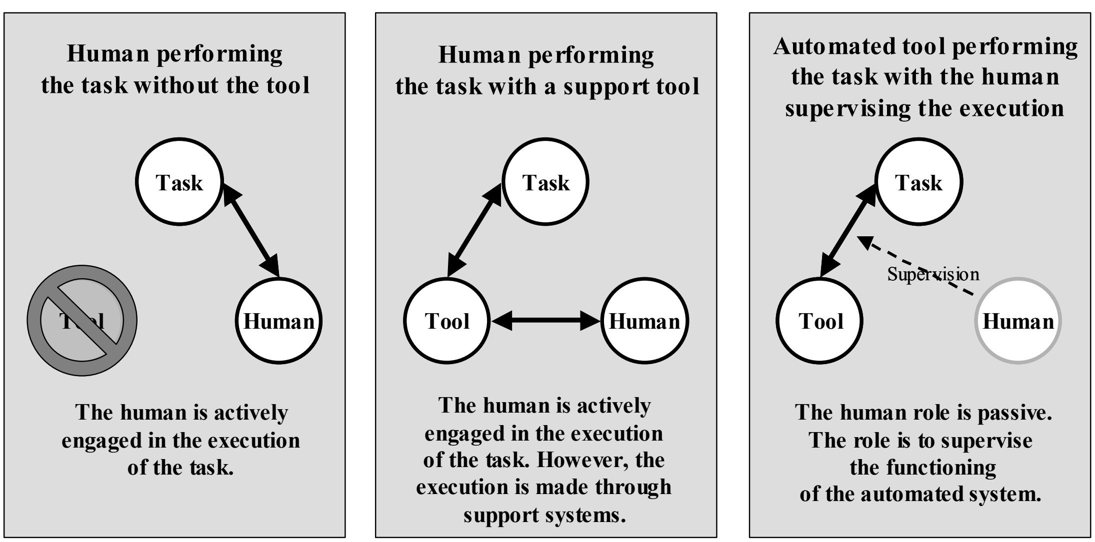

Figure 1: The Interaction between the Task, the Human and the Support or Automated Tool.

In the situations represented in the figure 1, let's assume that the task is clearly defined, but is performed in a challenging complex and stressful environment. Lets also assume that the human possesses all the expertise to execute the given task, and the tools are appropriately designed to support or automate the execution of the task.

The left part of the figure 1 represents a situation where no support or automated tools are available to the human. In this situation, the human takes completely charge of the execution of the task. The human must process the information and use the appropriate cognitive processes in order to successfully execute the given task. The middle part of the figure represents a task executed with the support of a tool. In that particular situation, the human is still in charge of the execution of the task. However, the tool supports some parts of the task. An optimal situation is reached when the tool supports the human where his cognitive capabilities are not sufficient to adequately perform the task. As it is illustrated, the human executes the task through the tool. The tool becomes the interface between the human and the task. An important aspect in this situation is to establish an optimal interaction between the tool and the human. In the context of the execution of a decision-making task, the processes supported by the decision aid must be familiar to the human and be appropriate to the situation at hand (Smith & Marshall, 1997). Smith and Marshall raise the importance of a rich interaction between the user and the decision aid. They also suggest that this can only occur if the user is able to relate to the aid and the processes it represents. Therefore, compatibility between the system and the human decision-making processes is required. The right part of the figure represents a situation where the task is executed by an automated system. In that situation, the human role is modified from an active one (left and middle parts of the figure) to a supervisory one. The role of the human is to supervise the execution of the task supported by the automated tool.

On one hand, the complexity and the tempo of the environment ask for the automation to successfully fulfil the mission. On the other hand, the modification of the human role in the execution of the task must have to be analyzed to identify potential cognitive costs. The new passive role attributed to the human may have an impact on his ability to understand the situation and to build an appropriate mental model of the situation that is essential to recover from system failure or to cope with unexpected events that cannot be processed by the automated system. Then, the analysis is based on these following factors:

- the level of workload,
- the attentional resources required from the human,
- the reduction of the stress and fatigue factors,
- the reduction of human error occurrence,
- the quality of situation understanding by the human,
- the human capacity to recover from system failure or the occurrence of unexpected events,
- and the role of the human in the execution of the overall decision-making task.

The Decomposition of the Decision Making in C^2 Environment: The OODA Loop Model

In the literature, the Boyd's OODA loop (Observe-Orient-Decide-Act) is generally accepted to represent the generic processes that lead to the decision and the implementation of the course of actions chosen in command and control situations. The OODA loop model has been specifically developed to represent the decision-making process of aircraft pilots in combat situation.

There are two major problems related to the OODA loop representation:

1. Although the Boyd's OODA loop representation suggests that the processes are executed sequentially (see figure 2), these processes may also be executed concurrently. In fact, it may have numerous cycles between the Observe and the Orient processes that improve the comprehension of the situation with the numerous iterations (see figure 3). This iteration process stops by a time constraint (time to decide elapsed) or when the level of uncertainty is no more reduced by further iteration. Then, a decision is taken (Decide) and the course of actions is implemented (Act).

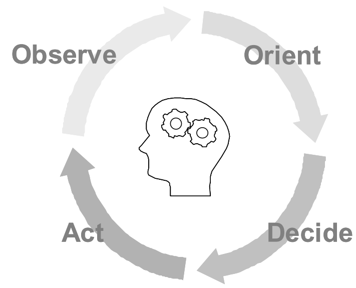

Figure 2: The OODA (Observe-Orient-Decide-Act) Loop.

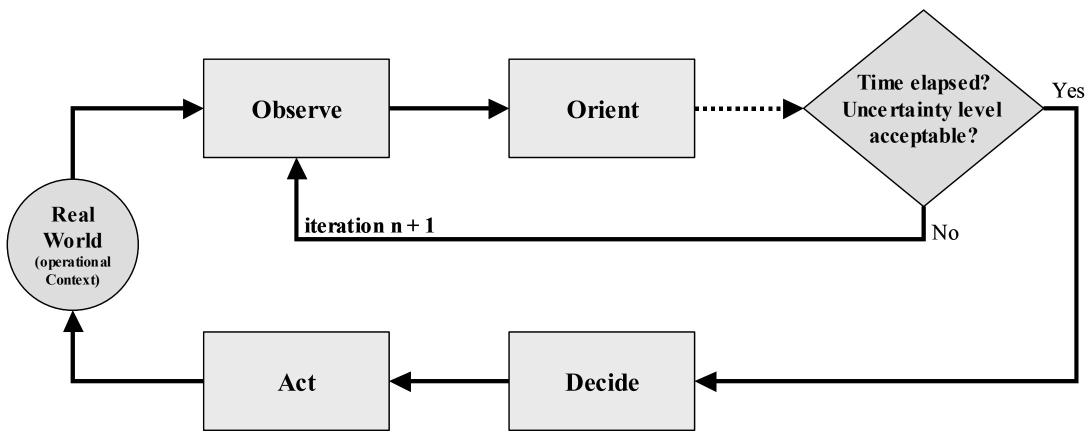

Figure 3: The Dynamic Representation of the OODA Loop.

2. Because of the abstract description of the OODA loop processes, it is difficult to identify design requirements for support systems or to elaborate training programs to improve the human decision-making performance from this general representation. The cognitive processes that sustain the activities describe by the OODA loop must be identified as well as their limitations and capacities.

Keus and Breton (in preparation) have proposed a detailed version of the OODA illustrated in the figure 4. According to this model, information is gathered from the environment (real world) by technological devices such as sensors or radars. These different sources of information are presented through technological displays to the decision-maker. From a pattern recognition process, the decision-maker recognizes familiar and meaningful features. Features are meaningful and familiar if in the decision-maker long-term memory, a mental model that matches the situation can be activated. The concept of mental models has a very long tradition in applied cognition. It has often been used in studies trying to model, amongst others, human control of various processes. Unfortunately, the concept has been used in so many contexts that it has resulted in certain confusion. Rouse & Morris (1986) define mental models as with three different functions. Mental models are the mechanisms whereby humans are able to generate descriptions of system purpose and form; explanation of system functioning and observed system states; and predictions of future system states.

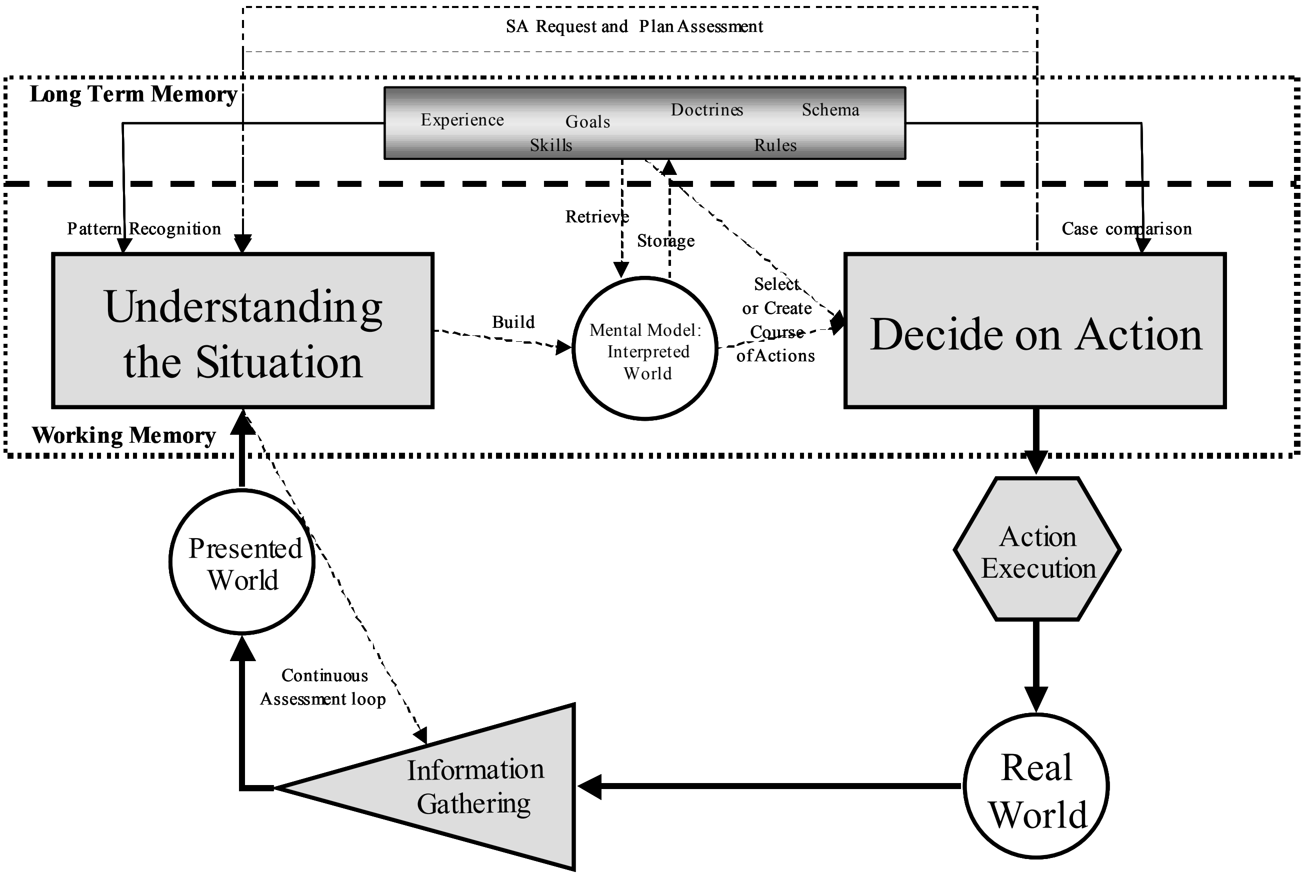

Figure 4: The Decision Process Model Proposed by Keus and Breton (in preparation).

In the case where no mental models are available to understand the situation, a new mental model can be built according to the information presented by the systems and previous knowledge and experiences stored in the decision-maker long-term memory. Through mental simulation including cases comparison, a potential course of action defined by the new mental model can be tested to evaluate its viability. If the results of the mental simulation reveal no potential problem, a course of action can be selected and the relevant actions can be implemented. The new mental model as well as the results of its implementation is stored in the long-term memory as a new experience. This learning process may define the development of the expertise.

The Automation of the Decision-Making Processes

The model proposed by Keus and Breton is based on three simple input-process-output modules that are interrelated by each other (see figures 5, 6 and 7). The output of a module becomes the input for the next one. The automation can be applied to each of these modules. Figure 5 describes a situation where only the information gathering process (first module) is automated. This process can be automated by information fusion systems involving numerous sensors. The automation of the information gathering process allows the processing of multiple sources of information that would exceed the human capabilities. In this situation, the human has still the responsibility of understanding the situation (second module) and to decide according to the mental model developed (interpreted world) which course of action is suitable (third module). Because the human has the responsibility of the execution of two modules, the workload is still important and the attentional resources required to process the information presented by the display could be considerable. Moreover, the performance is also subject to the influence of fatigue, stress and is error prone. However, the active role of the human in the understanding of the situation module allows him to build an adequate mental model based on the information gathered by the automated systems from the environment. This mental model can allow him to recover from system failures or to rapidly identify unexpected events and to adequately react to them.

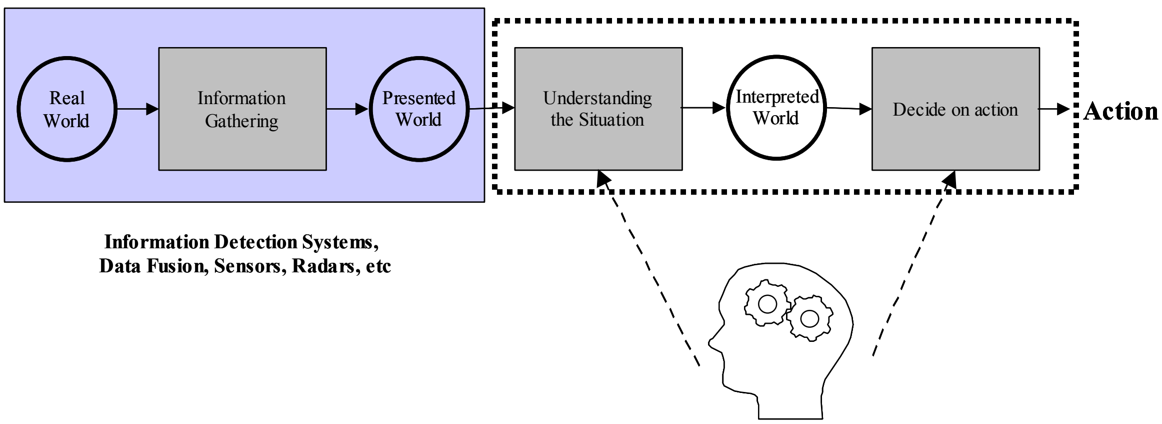

Figure 5: The Automation of the Information Gathering Process.

Figure 6 presents a situation where the first two modules (information gathering and understanding of the situation) are automated. The automation of these two processes can be performed by the application of information fusion, pattern recognition and identification processes, etc. The automation of the information gathering process allows the processing of multiple sources of information that would exceed the human capabilities. The information-processing load imposed to the human is significantly reduced as well as the demands to the attentional resources. The automation of the understanding of the situation module allows the rapid and accurate activation of an appropriate case that is stored in a database and fits to the situation. The automation increases the stability of the performance by the reduction of the effect of stress and fatigue that only affect the human. By automating complex and error prone parts of the task, the probability of human errors is considerably reduced. In this particular situation, the human contribution is restricted to the selection of the course of action based on the picture of the situation depicted by the automated systems. The automated system provides an evaluation of the situation and the decision-maker must select the most appropriate course of actions. However, since the understanding of the situation module is automated and the human implication is restricted to the selection of the course of action, one may assume that the human understanding of the situation may be only superficial. Consequently, the mental model activated from the long-term memory can be incomplete or in the worst case inaccurate. This situation can be problematic in case of system failure or the occurrence of unexpected events.

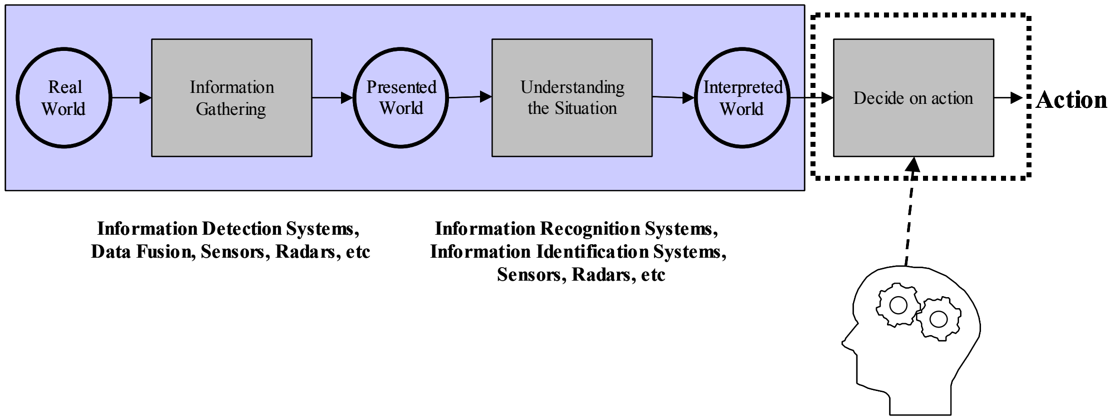

Figure 6: The Automation of the Information Gathering and the Understanding of the Situation Tasks.

Figure 7 represents the situation where all the processes leading to the selection of a course of action and the implementation of the action are automated. Automated systems based on knowledge-based, rules-based and case-based reasoning architecture can be applied to automatically select an alternative from a pool of options according to the result of the automated information gathering process and the automated understanding of the situation process. In this situation, the human task is to supervise the execution of the tasks by the automated systems. Since, the tasks are totally performed by the automated tools, the mental workload is reduced to a minimal level as well as the attentional resources that the human has to devote to the execution of task. Since, the tools are not affected by the fatigue and stress, these two human factors are not influencing the performance. Also, since the human implication is reduced at a minimal, the probability of human errors is reduced to a minimum. Then, the performance is very stable. A negative side effect of the automation is related to the role attributed to the human. The passive role of supervisor attributed to the human can reduce his capability to develop an adequate mental model that is crucial to overcome system failures.

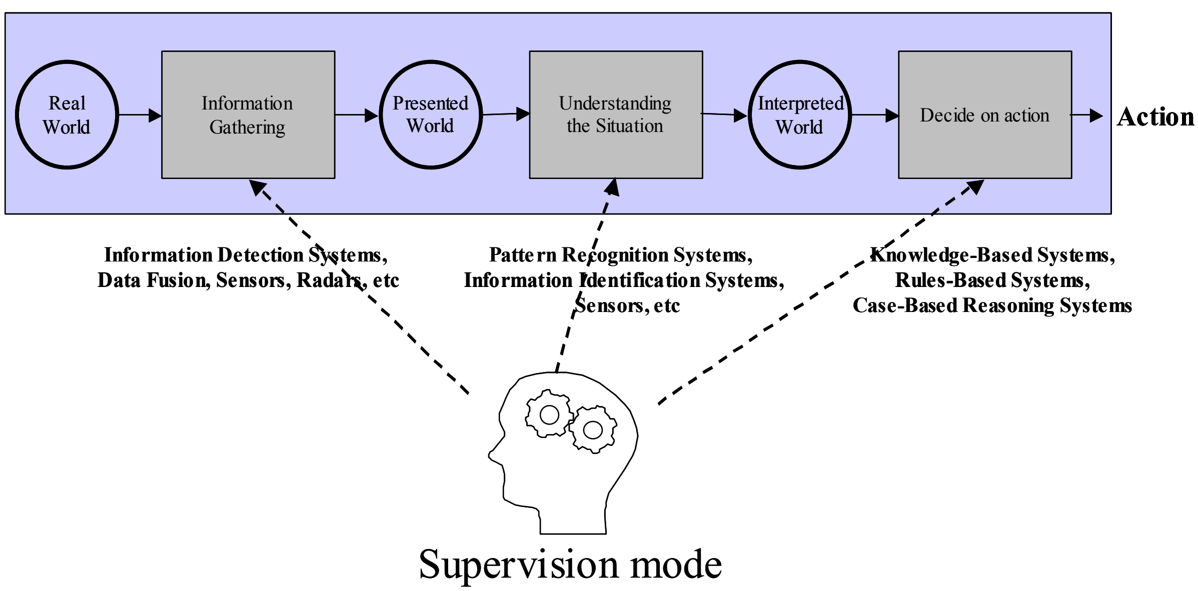

Figure 7: The Automation of all the Processes Leading to the Action Implementation.

Table 1 summarizes the comparison between the three basic situations describes above according to the level of mental workload, level of attentional resources required, the effect of stress and fatigue, the possibility for human errors, the capacity to build adequate situation awareness and the type of implication required by the human.

Table 1: Comparison between the Three Basic Situations represented in Figures 5, 6 and 7

Automation	Mental Workload	Attentional resources required	Effect of fatigue	Effect of Stress	Possibility of Human Errors	Mental Model	Capacity to recover from problems	Type of Implication
Figure 5	High	High	Potential	Potential	Probable	Excellent	Excellent	Primary Actor
Figure 6	Low	Low	Low	Low	Low	Poor	Difficult	Secondary Actor
Figure 7	Very Low	Very Low	None	None	None	Very Poor	Very Difficult	Supervisor

From the analysis of the table 1, a clear relationship can be identified between the level of involvement of the human in the execution of the decision-making task and the quality of the mental model that defines the level of situation awareness. When all the modules are executed completely by the human without the implication of automated tools, the very active implication allows him to reach an adequate level of understanding of the situation and consequently to build a complete and accurate mental model related to the situation at hand. The supervisory role attributed to the human with automated systems makes the development of the mental model difficult.

Obviously, the level of the implication of the human is highly influenced by the level of automation introduced in the environment. A tradeoff can be identified between the quality of the mental model and the level of automation. More automated is the execution of the task and less complete and accurate can the mental model be.

On one hand, the automation is essential to reduce the mental workload, attentional demands, the effect of fatigue and stress factors and the probability of errors. On the other hand, the automation may prevent the human supervisor to build an adequate mental model of the situation that is essential for the recovery of system failure and the processing of unexpected events. Systems designers are facing with the challenge of developing systems that own the benefits of the automation without preventing the development of the mental model. The next section presents a potential solution to this compromise.

Learning to Become an Adequate Supervisor

As mentioned above, the automation is essential in complex and challenging environment such as C^2. However, with automated systems, the human role is shifted to a supervisor one. The passive implication of the human in the execution of the decision-making can prevent him to develop a good understanding of the situation that is essential to recover from system failure or the occurrence of unpredicted events that cannot be overcome by the automated system. Consequently, automated systems must have to be introduced with cautious in the human environment.

As it can be seen with the decision process model proposed by Keus and Breton (in preparation), the decision-making task can be decomposed in three distinct input-process-output modules that are interrelated each other in a way that the output of one module becomes the input for the next one. Benefits are obtained by the automation of the process part of these modules. On the other hand, the cost of the automation (poor mental model) is also related to the passive implication of the human in the execution of these processes.

With automated systems, the human may have the perception that all the task execution is under the responsibility of the automated systems. In fact, this perception is not false. Automated systems are built to replace the human. However, it does not mean that the automated system functioning could not be supervised properly. There are two recommendations that should allow the human to adequately supervise the systems functioning.

First, a way to adequately supervise the automated systems is to understand how they are working. The interactions between machine agents need to become more transparent to allow the operators to stay informed about the activities of the overall joint human-machine team (Olson and Sarter, 2001). Then, the human supervisor should understand the basic under the automated systems. Without training the human to become an expert in the theories and applications that are used to design and develop the automated systems, training programs should be adapted to allow the human to understand the automated system functioning.

Second, coupled with an adequate understanding of the system functioning, the human should have access to the sources of information (input) that are processed by the automated systems. Consequently, these sources of information should be presented in a comprehensive and meaningful manner to the human. According to Olson and Sarter (2001), the challenge is for the automation to not merely provide additional data but to reduce the cognitive effort required to locate, integrate, and interpret those data (i.e. improve system observability). The availability of the information sources should allow him to build an adequate mental model of the situation. These two simple recommendations illustrated in the figure 8 should allow the human to adequately supervise the systems functioning and the evolution of the decision-making task.

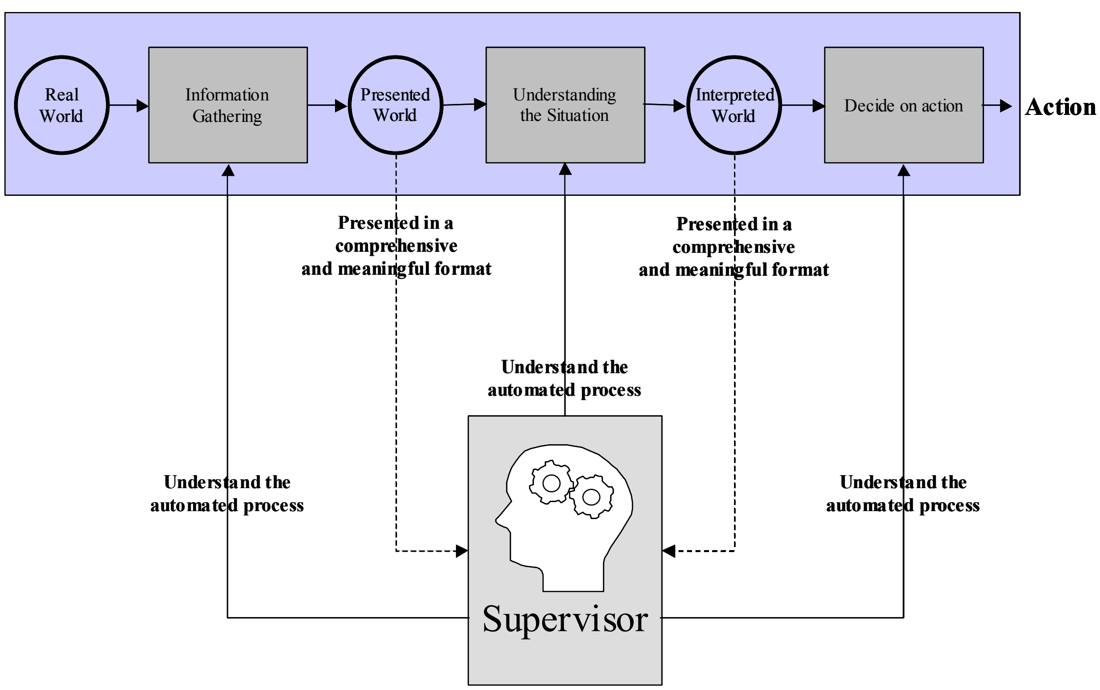

Figure 8: The Adequate Supervision of the Automated Systems.

According to Sarter and Woods (1997), pilots are forming expectations based on their knowledge of the input to the automated system in combination with their understanding of the functional structure of that system. When higher level of autonomy and authority are attributed to the automated systems, these systems can initiate actions independent of the human contribution or involvement. Consequently, changes in system status and behavior can occur because of inputs from other sources (i.e. sensors). In these situations, Sarter and Woods observe that it is far more difficult for pilots to keep track of or to form expectations about the events.

CONCLUSION

Automated systems are essential in complex and challenging environment such as C^2. Among the benefits related to the automation, we note:

- The reduction of the operator's workload.
- With automated systems, operator's attentional resources can be allocated to other tasks executed concurrently.
- The reduction of the stress factor induced by the stakes of the situation.
- The reduction of the fatigue factor.
- Automated systems provide a certain level of stability in the execution of a task.
- Automated systems eliminate human errors.

Unfortunately, some cognitive costs are also related to the introduction of automated systems into C^2 environment. Manual skills may deteriorate in the presence of long periods of automation (Wickens, 1992). Automation removes the human from the loop producing significant decreases in situation awareness (Sarter and Woods, 1992). Finally, over reliance on automation may make the human less aware of what the system is doing, leaving the human ill-equipped to deal with system failures (Scerbo, 1996). Consequently, a major cognitive cost is the impoverishment of the human understanding of the situation that is essential to activate or build an adequate mental model of the situation that is essential for the recovery of system failures or to cope with unexpected events that cannot be processed by the automated systems.

A potential solution to tackle the automated system introduction is to train the human to adequately supervise the system functioning. Human supervisor should understand how the system is working and they should have access to the information that is considered by the automated systems in order to develop, as the situation is evolving, an adequate understanding of this situation. The information considered by the automated system should be presented in a meaningful format to the human.

Consequently, training programs should be defined to help the human to become an adequate system supervisor by understanding the systems functioning. Automated systems should be designed to provide meaningful and significant information to the human supervisor.

REFERENCES

Breton, R., Rousseau, R. & Price, W.L. (2001). The Integration of Human Factors in the Design Process: A TRIAD Approach. Defence Research Establishment Valcartier, TM 2001-002, 33 pages.

Keus, H.E., & Breton, R. (in preparation). A Framework for the Analysis of Decision Processes in Teams.

Mosier, K.L. & Skitka (1996). Human Decision Makers and Automated Decision Aids: Made for Each Other? In R. Parasuraman & M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications (Series on Human Factors in Transportation)* (pp. 201-220). Mahwah, NJ: Lawrence Erlbaum Associates.

Olson, W.A., & Sarter, N.B. (2001). Management by Consent in Human-Machine Systems: When and Why it Breaks Down. *Human Factors*, 43, 255-266.

Rouse, W.B. & Morris, N.M. (1986). On Looking into the Black Box: Prospects and Limits in the Search for Mental Models. *Psychological Bulletin*, 100(3), 349-363.

Sarter, N.B., & Woods, D.D. (1992). Pilot Interaction with Cockpit Automation: Operational Experiences with the Flight Management System. *International Journal of Aviation Psychology,* 2, 303-322.

Sarter, N.B., & Woods, D.D. (1997). Team Play with a Powerful and Independent Agent: A Corpus of Operational Experiences and Automation Surprises on the Airbus A-320. *Human Factors*, 39, 553-569.

Scerbo, M.W. (1996). Theoretical Perspectives on Adaptive Automation. In R. Parasuraman & M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications (Series on Human Factors in Transportation)* (pp. 37-63). Mahwah, NJ: Lawrence Erlbaum Associates.

Smith, D.E., & Marshall, S. (1997). Applying Hybrid Models of Cognition in Decision Aids. In C. Zsambok, & G. Klein (Eds.), *Naturalistic Decision Making* (pp. 331-342). Mahwah, NJ: Lawrence Erlbaum.

Wickens, C.D. (1992). *Engineering Psychology and Human Performance* (2nd ed.). New York: HarperCollins.

This page has been deliberately left blank

Page intentionnellement blanche