Cognitive Control Modes and Mental Workload: An Experimental Approach

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Abstract: This study aims to examine the relationships between cognitive control modes and mental workload. It uses the Multi-Attribute Task Battery (MATB-II) microworld, which reproduced tasks carried out in an aircraft. Twenty participants performed a main task in different conditions defined by the level of complexity and the absence or presence of a secondary task. Two types of physiological data were considered as indicative of mental strain: cardiac activity and oxygenation and deoxygenation of the prefrontal cortex. Besides a classic relationship between mental stress and mental strain, this study draws attention to a relationship between the level of complexity and the control modes, which is highly significant for the tactical mode. Furthermore, this mode is associated with a significantly lower oxygen concentration than that found in the other modes, indicating lower mental strain. Hence, in this study, the tactical mode is found to be the most efficient one, since it is associated with a satisfying performance and with low mental strain. It is also the most impacted by task complexity. This finding should prompt an investigation of possible ways of supporting this mode in naturalistic situations.

1 INTRODUCTION

Monitoring and process control activities carried out in dynamic situations are characterized by the management of uncertainty and risk, the multiplicity of tasks, and the complexity of the controlled systems (Hoc, 1996). From a cognitive perspective, these activities call for diagnostic/prognostic and decision-making processes that use both internal data processing (i.e. mental models relating to the controlled systems or to environmental dynamics) and external data processing (i.e. information that is available in the environment or interfaces). Hence, in dynamic environments, the pilot of a mobile vehicle (e.g. aircraft, car, ship) is more or less proactive (when he/she relies on mental models to act) or more or less reactive (when his/her actions are mainly driven by external data). This behavioral flexibility is closely linked to the notion of cognitive control, which is at the center of two important models in the field of cognitive ergonomics: Rasmussen's Skills-Rules-Knowledge (SRK) model (Rasmussen, 1983) and Hollnagel's Contextual Control Model (COCOM) (Hollnagel, 1993). Those models are well-known. However, the different modes of control they identify have rarely been "quantified" or evaluated from a neurophysiological point of view (Borghini et al., 2017). Several questions arise concerning the relationships between the control mode that operators are likely to adopt and their performance but also concerning the control mode adopted and the operators' workload. This article investigates these issues.

2 COGNITIVE CONTROL AND MENTAL WORKLOAD

Cognitive control is one of the key concepts in contemporary cognitive neuroscience. It refers to

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processes that allow information processing and behavior to vary adaptively from moment to moment, depending on current goals, rather than remaining rigid and inflexible. Research conducted in cognitive neuroscience has identified two control modes (Braver, 2012). The proactive control mode is characterized by the maintenance of goal-relevant information in working memory, which optimizes attention, perception, and response preparation. It relies on a sustained activity of the dorsolateral prefrontal Cortex (dlPFC). In the reactive control mode, attention is mobilized as part of a late correction mechanism, and decision making is guided by stimuli (Mäki-Marttunen, Hagen, & Espeseth, 2019a). This mode of control is linked to a more transient activation of the dlPFC (Ryman, El Shaikh, Shaff, Hanlon, Dodd, Wertz, C. & Abrams, 2019). As summarized by Braver (2012, p. 106), "proactive control relies upon the anticipation and prevention of interference before it occurs, whereas reactive control relies upon the detection and resolution of interference after its onset". In the field of cognitive neuroscience, different experimental studies have shown a link between cognitive workload and cognitive control, as a heavy workload leads to the adoption of a reactive control mode (Mäki-Marttunen, Hagen, & Espeseth, 2019b).

In the field of cognitive ergonomics, two models of cognitive control have been proposed to account for the behavior of operators in dynamic situations: the SRK taxonomy of Rasmussen (1983) and the COCOM model proposed by Hollnagel (1993). As Hoc and Amalberti (2007) point out, these two models focus on two different aspects of cognitive control. The SRK taxonomy considers the level of abstraction of the data processed during supervision activities (sub-symbolic vs. symbolic data), whereas the COCOM model accounts for the more or less reactive or proactive nature of the observed behaviors.

The taxonomy defined by Rasmussen distinguishes three different levels of control. The skill-based level results in the implementation, without conscious attention, of cognitive automatisms and automated and strongly integrated patterns of actions. At the rule-based level, behavior is guided by known rules or procedures. The knowledge-based level is brought into play to solve new problems requiring the definition of new rules, innovation, and creativity. Cegarra et al. (2017) have shown that the skill-based level is associated with a lower mental load than the rule-based level.

The COCOM model puts the emphasis on temporality. It distinguishes among four main control modes (Hollnagel, 1993, 2002): strategic, tactical, opportunistic, and scrambled.

The strategic mode is used only when there is considerable time available. It involves managing several goals simultaneously and using predefined or generated plans in order to address a situation. Hence, it requires considerable attentional resources. The tactical mode is based upon using known rules and is used to process a limited number of goals. When the available time is only just sufficient, operators are likely to use an opportunistic mode that focuses on managing one goal only. Hence, the resulting choice of action is determined by the most salient information. Finally, the scrambled control mode is used when the time available is extremely limited. In that case, planning is impossible and the choice of action is random; consequently, the operators no longer control the situation.

A number of studies have already used the notion of control modes to account for operators' performance in dynamic situations (Stanton, Ashleigh, Roberts, & Xu, 2001; Eriksson & Stanton, 2017; Chauvin, Said, & Langlois, 2019), but, to our knowledge, the relationship existing between the four modes of the COCOM model and the mental workload of operators has not been investigated yet. The present study deals with this issue. It uses the Multi-Attribute Task Battery (MATB-II, Santiago et al., 2011) microworld to meet two goals: distinguishing different control modes and examining the relationship between control mode and mental workload.

Following the ergonomics principles of standard DIN ISO 10075-1:2017 (2018), mental workload is viewed from both aspects of mental stress (i.e. the constraints imposed upon operators) and mental strain (i.e. the cognitive cost of the task for the operators).

3 METHOD

The experiment used the MATB-II microworld, which has already been used to examine the relations between cognitive control modes and mental workload (Cegarra, Baracat, Calmettes, Matton & Capa, 2017). In this previous study, the notion of cognitive control was viewed from the perspective of Rasmussen's (1983) SRK taxonomy. Hoc and Amalberti (2007) explain that the SRK taxonomy deals with an aspect of cognitive control that involves the level of abstraction of the data processed as part of monitoring activities (i.e. sub-symbolic or symbolic data). In the present study, another aspect of cognitive control is focused on, namely the source of the data being processed: proactive control involves internal data (i.e. mental models), whereas reactive control involves external data.

The experiment entailed asking participants to execute a main task for which optimum performance would require adopting a strategic mode; the task involved managing the content of fuel tanks. The task was repeated three times, and its complexity (i.e. mental stress) increased each time.

3.1 Participants

Twenty participants in the 18-21 age group (M = 18.55; SD = 0.83), all male, were recruited from among the student population of Université Bretagne Sud. All showed normal hearing and normal vision (or corrected to normal vision). The participants were informed of their rights and provided written consent for their participation, in line with the Helsinki Declaration.

3.2 Experimental Set-up

Participants were asked to perform tasks in the MATB-II environment shown in Figure 1. MATB-II is a microworld that enables people to execute four tasks that are characteristic of flying an aircraft. In this experiment, one of these tasks was used as a "main task".

The communication task was excluded from the protocol because it involves listening to an audio message in English, which could bring about a bias effect due to the heterogeneity of the linguistic level of our participants.

The main task, called "Resource management", simulated process monitoring. It involved the fuel management of a civil aircraft, using a set of six fuel tanks and the pumps that connect them. The instructions were to keep both upper tanks at a stable level of 2,500 units (symbolized by blue marks on the tanks), keeping in mind that the level was automatically reduced to simulate the fuel consumption of the engines. To do so, both tanks needed to be continuously supplied from the other tanks through the pumps that, however, could break down.

The secondary tasks were as follows: a tracking task that involved keeping a target at the center of a marker, and a system monitoring task that involved spotting anomalies in the position of markers (see the dial in the upper left corner of Figure 1). For this monitoring task, six parameters needed to be

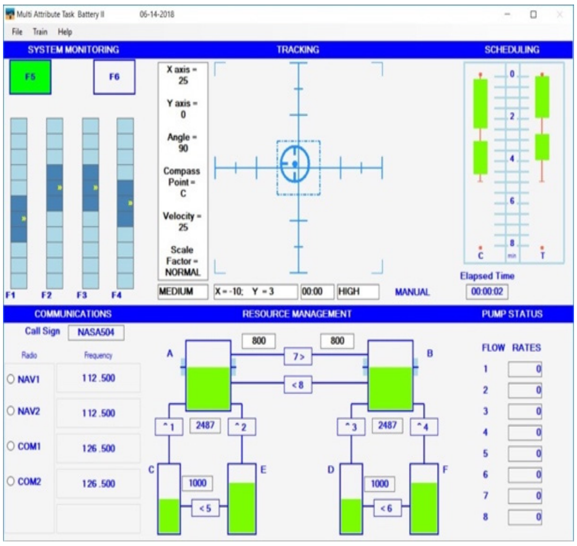

Figure 1: Screen capture of the MATB-II window.

monitored; they related to the colors of the boxes and the position of the marks on the scale. The top two boxes should normally be green for the left one, and white for the right one. The bottom four marks should be approximately in the middle of each scale. Deviations could be observed: the top two boxes could change color (red for the left one, green for the right one), and the bottom marks could move and touch the extremities of each scale. These deviations represent abnormal situations that must be remedied by pressing the key corresponding to the incriminated element: F5 and F6 for the top boxes, F1 to F4 for the bottom scales. Participants needed to press these keys within a time budget of 30 seconds.

3.3 Experimental Protocol

A preliminary phase was used to explain the tasks to be executed during a 15-minute training session followed by a test session aimed at ensuring that participants had fully understood the instructions.

The experimental phase was broken down into three 7-minute sequences (see Figure 2).

The first sequence involved the main task only (referred to as “resman”), the second one involved the main task and the secondary system monitoring task (named “with track”), and the third one required participants to execute both the main task and the secondary tracking task (named “with sysmon”).

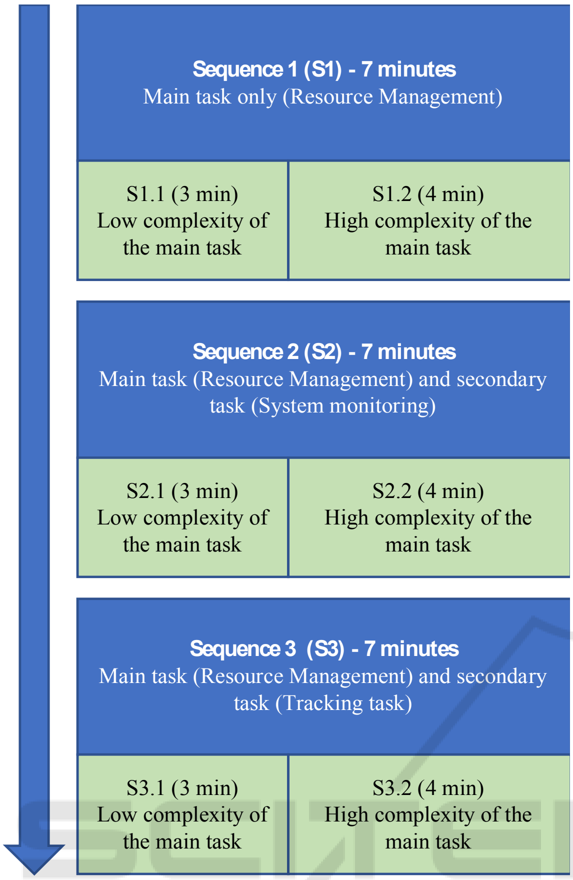

Figure 2: Three experimental sequences, each with two levels of complexity of the main task.

It should be noted that the main task ("resman") was a continuous task, since the participants had to manage the levels of the two reservoirs that changed every second, and whose dynamics (filling or emptying) could change when failures occurred. Furthermore, as explained by Philips et al. (2007) and Gutzwiler and Wickens (2015), we can also distinguish the two different secondary tasks of our scenario: tracking is a continuous task, which requires permanent control of the trajectory, whereas the monitoring system is a discrete task, consisting of acknowledging alarms when they appear on the screen. Thus, the succession of sequences in our scenario resulted in an increase in difficulty: first there was a continuous task alone, then a continuous task with a discrete task (generating "discrete" stimuli occasionally disturbing the participants in the main task), and finally two continuous tasks (which required the control of two processes whose dynamic evolution must be managed).

Furthermore, Figure 2 shows that each sequence itself was broken down into two periods: one 3-minute period during which executing the main task was less complex and a second 4-minute period during which the long breakdown of one pump made the task more complex.

At the end of each 7-minute sequence, a NASA-TLX questionnaire was given to the participants through the MATB interface.

3.4 Measures and Coding

The performance of the main task was coded to identify the modes of cognitive control likely to be adopted by the operator. To do this, we examined whether the participants complied with the instructions for the task (i.e. keeping the level of each of the two reservoirs between 2000L and 3000L), and how they managed their safety margin in relation to the low threshold of 2000L (the low threshold was more difficult to comply with than the high threshold, since pump failures accelerated the emptying of the reservoirs). Table 1 shows the characteristics of the operations used to operationalize each control mode likely to be used for the main task of fuel tank management. In accordance with Hollnagel's model, the strategic and the tactical modes are associated with a satisfying performance, whereas the opportunistic mode is associated with some errors and the scrambled mode with a poor performance.

Table 1: Characteristics of the control modes.

Control mode	Performance
Strategic	Complying with instructions and high margins for at least one of the two tanks (maximum upper value between 2,750 and 3,000)
Tactical	Complying with instructions and lower margins for both tanks (values oscillate between 2,000 and 2,750 around the target value of 2,500).
Opportunistic	Errors for at least one tank; the participant takes action when the minimal value (between 2,000 and 1,950) is exceeded
Scrambled	Serious errors for at least one tank; the minimum value (inferior to 1,950) or the maximum value (superior to 3,050) is exceeded by a large margin when the participant intervenes.

Two types of physiological data were collected and analyzed as indicative of mental strain: cardiac activity with Bioharness 3 belt (Zephyr, Medtronic, Ireland), and oxygenation and deoxygenation of the prefrontal cortex with the 8-channel functional near-infrared spectroscopy (fNIRS) system (Octamon, Artinis Medical, Netherlands). These sensors were especially chosen for their known and robust relationships with mental strain (see Table 2), as well as their ease of implementation in real world application (without too many interferences with ambient factors, such as light variations. The processing of fNIRS data was performed using a bandpass filter (0.01hz-0.09hz). To select the cutoff frequencies, we followed the approach of Pinti et al. (2019), which advocates a low frequency of 0.01hz and a high frequency lower than the Mayer wave frequency (0.01hz).

Table 2: Relationships between neurophysiological indicators and mental strain.

	Indicators
Cardiac activity	Heart rate variability (HRV), computed within time-domain parameters with the standard deviations over 100 successive RR intervals *Relationship with mental strain* Decreases with an increased mental workload (Malik, 1996, Durantin et al., 2014)
Prefrontal Cortex activity	Concentrations of oxygenated hemoglobin (HBO2) and deoxygenated hemoglobin (HBB) on the 8 optodes of the Fnirs. T1 to T4 capture relative changes in cerebral activation of the right hemisphere of the prefrontal cortex (PFC), and T5 to T8 capture changes in the left hemisphere. Specifically, T1-T7 capture changes in the dorsolateral PFC, T2-T8 capture changes in the ventrolateral PFC, T3-T5 capture changes in the ventromedial PFC, and T4-T6 capture changes in the orbitofrontal PFC. *Relationship with mental strain* Neuronal activity is associated with an increase in concentration of oxygenated hemoglobin and a decrease in deoxygenated hemoglobin (Fairclough et al., 2018, Causse et al., 2019)

3.5 Data Analysis Method

The analyses conducted are part of an exploratory study. We used a two-step methodology to analyze the data. Bhapkar and McNemar analyses were conducted to investigate possible links between mental stress (viewed as an independent variable) and control mode (viewed as a dependent variable). Additionally, we used R (R Core Team, 2012), and especially the lme4 package (Bates, Maechler & Bolker, 2012), to perform linear mixed effects analyses of the relationship between sequence and complexity (viewed as independent variables) and the neurophysiological indicators presented in Table 2 (viewed as dependent variables). Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. As fixed effects, we entered sequence (single or double task), complexity (low or high, corresponding to whether the main task had few or many incidents on the pumps) and cognitive control mode (with interaction terms) into the full model. As random effect, we had intercept for participants. Regarding fixed effects, a stepwise model selection by AIC (stepAIC) was conducted. During each step, a new model was fitted, in which one of the model terms was eliminated and tested against the former model.

4 RESULTS

4.1 Effect of Mental Stress upon the Control Modes

First, we conducted a multinomial logistic regression between control modes and the two factors related to mental stress (sequence and complexity). No effects of interaction were found between these two factors. Next, we examined the effect of the complexity of the main task by comparing the control modes adopted when complexity is low (first period) and when it is more important (second period) as shown in Table 3.

Table 3: Contingency table crossing complexity levels and cognitive modes of control.

	Scrambled mode	Opport. mode	Tactical mode	Strategic mode
Low Complexity	4	3	26	23
High Complexity	15	10	3	28

We observed that tactical and strategic modes are largely adopted when the task complexity is low. The strategic mode is still used when the complexity increases but the tactical mode disappears.

A Bhapkar test revealed that the level of complexity has a significant effect on the control mode regardless of the secondary task: resman ($\chi2(3, 19) = 30.38$, $p < 0.001$), resman with sysmon ($\chi2(3, 19) = 11.08$, $p = 0.01$), and resman with track ($\chi2(3, 18) = 20.79$, $p < 0.001$). McNemar post-hoc tests with Bonferroni adjustment revealed that, for the main task alone (resman), the scrambled mode is significantly more frequent when the level of complexity is high ($p = .03$). Besides, the tactical mode is significantly more frequent in tasks with low complexity level than in tasks with high complexity level: resman (p <.001), resman with sysmon (p=.043) and resman with track (p = .019).

The probability of moving from an X mode when the complexity is low to a Y mode when the complexity is higher was calculated from a transition matrix (see Table 4).

Table 4: Matrix of transition between the mode adopted when complexity is low and the mode adopted when complexity is high.

Low ↓/ High →	Sc	O	T	St	Total
Sc	4				4
O	3				3
T	5	9	3	9	26
St	3	1		19	23

(Sc = Scrambled, O = Opportunistic, T = Tactical, St = Strategic)

Examining the transitions between the two periods (hence between the two complexity levels) shows (see Figure 3) the stability of the strategic mode (among the 23 participants who adopted the strategic mode in the first period, 19 maintained it in the second one) and the instability of the tactical mode (among the 26 participants who adopted the tactical mode in the first period, only 3 maintained it in the second one).

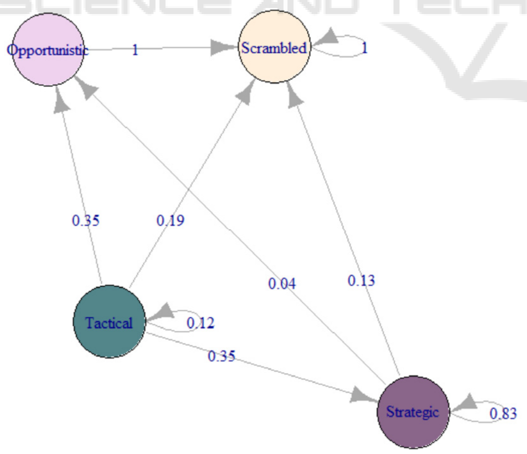

Figure 3: Transitions between modes between the periods of low complexity of the main task (S1.1, S2.1, S3.1) and the periods of greater complexity (S1.2, S2.2, S3.2).

In contrast, the comparisons conducted for each complexity level between sequence 1 (main task alone) and sequences 2 and 3 (main task and secondary tasks of system monitoring and tracking) do not show any negative effect of the secondary task upon the control modes. As a matter of fact, the majority of participants kept the control mode they had adopted for sequence 1 (main task alone), or else they adopted a more effective control mode, which shows the effect of learning.

4.2 Relations between Mental Stress and Mental Strain

We conducted different linear mixed-effect analyses to test the effects of task, complexity and cognitive control modes (CCM) on physiological responses. The significant effects (figures in bold in Table 5) are given relative to the reference condition. For example, we can observe the effect of the sequence on HRV, which decreases by 13.72 ms between the single task condition "resman" only" and dual task condition "resman with sysmon", and by 12.46 ms between the single task condition and "resman with tracking" (see Table 5 and the left part of Figure 4).

These analyses show that HRV can be explained by mental stress, i.e. by sequence, complexity and their interactions (see Table 5 and Figure 4).

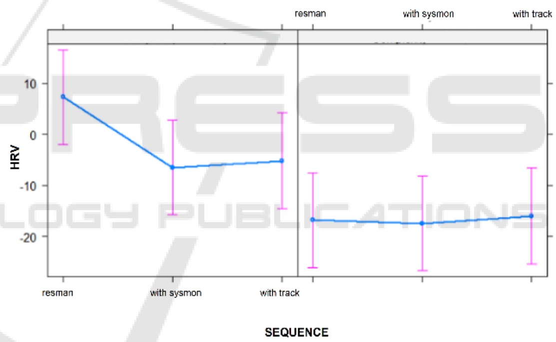

Figure 4: Interactions of sequence and complexity on HRV.

We found a significant main effect of complexity, with HRV more likely to decrease in the high complexity than in the low complexity condition (β=-24.03, SE=3.60, t(63)=-6.67, p<0.001). Moreover, there is also a significant effect of sequence. We found lower HRV when the main task was carried out with the secondary tracking task (β=-12.46, SE=3.69, t(63)=-3.38, p<0.01) or with system monitoring task (β=-13.72, SE=3.60, t(63)=-3.81, p<0.001), than when it was conducted as a single task.

This effect of sequence upon operator strain is also observed, on the mental demand dimension of the NASA-TLX. A one-way between subjects ANOVA shows that the single task condition involved a significantly lower mental demand than the double task conditions (F(2,48)=4.32, p<0.05). The interaction between complexity and sequence is

Table 5: Estimates of fixed effects from linear mixed-effect model for HB02 on the 8 fNIRS optodes and for HRV.

	HBO2 T1 ~ CCM + Sequence	*HBO2 T2 ~ CCM*	*HBO2 T3 ~ CCM*	*HBO2 T4 ~ CCM + Sequence*	*HBO2 T5 ~ CCM*	*HBO2 T6 ~ CCM*	*HBO2 T7 ~ CCM*	*HRV ~ Complexity * Sequence*
(Intercept)	0.13 (1.66)	**3.08** (0.95)**	0.26 (2.56)	1.39 (1.16)	0.36 (2.53)	**2.66** (0.95)**	1.35 (0.94)	7.25 (4.66)
CCM (reference = Tactical)								
Opportunistic	**0.94** (0.21)***	**1.11** (0.32)***	**0.69** (0.30)*	**0.99** (0.34)**	0.48 (0.29)	**0.97** (0.32)**	**0.59** (0.28)*	
Scrambled	**1.08** (0.24)***	**0.71** (0.36)*	**1.26** (0.33)***	**0.84** (0.39)*	0.62 (0.33)$^{.}$	**0.85** (0.35)*	**0.71** (0.32)*	
Strategic	**0.63** (0.18)***	**0.78** (0.27)**	**0.76** (0.25)**	0.53 (0.29)$^{.}$	**0.71** (0.25)**	**0.74** (0.27)**	**0.79** (0.24)**	
Sequence (reference = single task resman)								
with sysmon	0.23 (0.15)			0.30 (0.24)				**-13.72** (3.60)***
with track	**0.48** (0.15)**			**0.69** (0.24)**				**-12.46** (3.69)***
Complexity (reference = low complexity)								
high complexity								**-24.03** (3.60)***
Sequence:Complexity								
with sysmon : high complexity								**13.07** (5.09)*
with track: high complexity								**13.24** (5.19)*
Num. obs.	100	100	100	100	100	100	100	82
Num. groups: Participant_	17	17	17	17	17	17	17	14
Var: Participant_ (Intercept)	46.61	14.82	110.76	21.72	108.17	14.62	14.52	212.55
Var: Residual	0.36	0.82	0.70	0.93	0.69	0.80	0.64	90.84

Note. The fixed factors resulting from the stepwise model selection by AIC are indicated below the response variables; the reference condition is indicated in brackets for each explanatory factor; $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$.

also found to be significant, with a higher contrast between single task and double task conditions when the complexity is low. Moreover, there is no significant correlation between neurophysiological indicators and NASA-TLX scores.

4.3 Relations between Control Modes and Mental Strain

The linear mixed-effect analyses also showed a significant effect of the control modes (CCM) upon the concentration in oxy-hemoglobin (HBO2). According to the stepwise model selection by AIC, HBO2 can be explained by control modes only, for optodes T2, T3, T5, T6 and T7, whereas HBO2 for optodes T1 and T4 can be explained by two main fixed effects, CCM and sequence. We followed the same procedure for concentration in deoxy-hemoglobin (HBB), but no significant results were found.

It should be noted that, for all the optodes from T1 to T7, the tactical control mode (set as reference condition in the linear mixed model) always produces a significant lower HBO2 concentration, in comparison with the less effective modes (scrambled and opportunistic control) or the more anticipatory one (strategic control).

5 DISCUSSION

The study findings are both theoretical and methodological in nature.

First, regarding the stress-strain relationship, we observed a significant effect of mental stress on HRV, which is unsurprising. There is a main effect of the complexity of the reservoir management task on cardiac activity. The other constraint factor of sequence (i.e. the addition of a secondary task) also plays a significant but lesser role when the complexity of the main task is low. We should also note that the neurological indicators (fNIRS) are not or not very sensitive to the constraint.

In addition, we investigated, in a more original way, the relation between the cognitive control modes and mental workload, from the perspective of both mental stress and mental strain. Our analyses reveal two main theoretical contributions.

On the one hand, there is a significant effect of task complexity on the adoption and the variation of control modes. In particular, we found an instability of the tactical mode, showing attraction between this mode and low complexity, and repulsion between this mode and higher complexity. This instability of the tactical mode was also analyzed with the finer-grained analysis of transitions between the consecutive periods of low and higher complexity. We observed that an increase in complexity mainly leads to transitions from the tactical mode to a less effective mode (54% of the transitions). In contrast, the strategic and scrambled modes were mostly stable (respectively 83% and 100% of participants in one of this mode remained in the same mode, between low and high complexity periods within a given sequence). Furthermore, and congruent with the study of Stanton et al. (2001), we observed that a major part of the transition is between two “close” modes (70% of transitions from tactical to opportunistic or strategic modes, and 100% of transitions from opportunistic to scrambled modes). This result suggests that people move between control modes in a linear manner.

On the other hand, we found links between the modes of control and operator strain, as it was shown by Cegarra et al. (2017). The present study indicates that the tactical mode is associated with lower mental strain, when considering the HBO2 concentrationndicator of mental workload. As stated by Leon-Carrion et al. (2008), “the hemodynamics of inter-individual differences in this region may reflect different cognitive strategies used in task resolution”. Our study shows that the tactical mode is the most efficient one, since it is associated with a satisfying performance and with the lowest mental strain off all control modes.

This result calls attention to the advantage of studying brain activity to detect changes in control mode. If, in our study, the cerebral activity seems little correlated with mental stress variations, we nevertheless observe, on almost all the zones of the prefrontal cortex, a significant difference in HBO2 concentration between the tactical mode and other modes. Hence, an increase in cortical activation could help reveal the shift away from the tactical mode towards less effective and more reactive control (the opportunistic or scrambled mode, where control of the situation is no longer guaranteed) or on the contrary towards more proactive control (the strategic mode, requiring more anticipation). This potential detection ability opens new perspectives to design and trigger assistance aimed at keeping operators in the tactical mode, since it appears to be the most efficient one. Such perspectives are worth considering in all areas where operators have to control dynamic situations and where they have therefore to make, in real time, compromises between speed and efficiency, between performance and risk, or between understanding and action (Hoc, 2000). Such circumstances cover the field of transport but also the supervision of industrial processes, the medical field (anesthesia in particular), or the field of crisis management.

Finally, it should be noted that this research work has some limitations. The experiment was run with novice participants only, who may be more heterogeneous in terms of cognitive control than an expert population. One may thus wonder whether some individual factors might not explain the propensity of some participants to adopt a particular control mode. Therefore, it would be necessary to verify whether the same findings would apply to experts (e.g. a population of aircraft pilots).

In addition, our study, which involved only male participants, may hide gender effects on the adoption of control methods. Moreover, we coded the four control modes of the COCOM according to operators’ performance on the main task and not the overall performance in the case of double task situations. When participants had to carry out multiple tasks, there could have been phenomena of focusing on or prioritizing the main task. This focus may have led to the maintenance of an effective cognitive control on the management of the reservoirs, to the detriment of the control of the secondary tasks. Hence, in future research studies, it would be worth considering cognitive control by adopting an approach modeling operators’ multi-task management on MATB-II, as proposed by Gutzwiller et al. (2014).

Finally, we did not control the chronobiological aspects in this study (i.e. food or caffeine intake before the test, or sleep duration the night before the experiment). We also did not measure the level of fatigue during the different phases of the experiment. It would be worth considering these elements in the future to analyze the relationship between fatigue and control modes and to explain the performance variations observed over time during the experimental scenario.

6 CONCLUSION

As part of an experiment on the MATB-II platform, this study investigates the relationship between cognitive control modes and mental workload. As shown in Figure 5, the control modes of the COCOM could enable regulating operators' mental workload, which would moderate the stress-strain relationship (Hockey, 1997; Kostenko et al., 2016; Cegarra, 2017). Higher mental stress may induce operators to leave the tactical mode, which can be detected through the fNIRS system. Leaving the tactical mode towards more degraded and reactive control (i.e. the scrambled or opportunistic modes), or on the contrary more elaborate and more proactive control (i.e. the strategic mode), could also explain the increase in operators' strain that is observed at the physiological level with the HRV indicator. Finally, the potential ability of fNIRS system to detect the tactical mode with HBO2 concentration could, in the future, help trigger adaptive assistance in order to keep operators in this efficient mode.

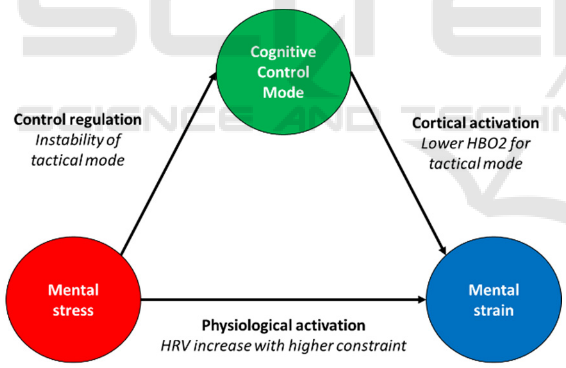

Figure 5: Towards a moderating effect of control mode on the stress-strain relationship.

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