Situation Awareness and Workload: Birds of a Feather?

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1. SUMMARY

In this paper it is argued that an hierarchical information processing model, with a basis in perceptual control theory, provides the necessary framework for interpreting a large, unfocused empirical literature on the topics of workload and situation(al) awareness (SA). The fundamental importance of situation awareness will emerge in considering the role of the mental model in providing the reference signal for a closed loop perceptual control system. It will be asserted that those aspects of the mental model generally covered by the SA rubric result from high level information processing activity that requires spare capacity to service. Increasing time pressure (workload) reduces the capacity available for this activity. An experiment in the application of a workload scale (NASA TLX) and a situation awareness metric (SART) to a simulated air traffic control environment is cited. It will be shown that the situation awareness scale taps largely into the workload side of the equation rather than the SA side. Implications for the measurement of SA will be drawn.

2. INTRODUCTION

Consider the following statement

In the ideal cockpit we would like aircrew to develop high levels of situation awareness using their cognitively compatible displays while experiencing low levels of task induced workload and achieving optimal, error free, performance.

Is this a reasonable goal for the systems designer? What are the relationships between the hypothetical constructs of *situation awareness* and *workload* and how is *performance* dependent on these concepts? Is *cognitive compatibility* part of this puzzle, and where is the theoretical framework that binds these ideas together? This paper attempts to provide such a framework, and argues that these concepts are less *birds of a feather,* but rather they are components of the same bird.

In many industrial and military systems, the potential for an operator to perform effectively when responding to novel situations such as malfunctions, emergencies, and unexpected occurrences depends on their knowledge of the moment to moment changes in the status of pertinent system variables, their deviation from a set of desired states or goals, the dynamics of the controlled system and the interactions between system variables. This knowledge forms an *internal representation* or *mental model* of the process to be controlled. The concept of a *mental model*, which the operator develops and draws upon when making operational decisions, is central to the idea of *situation awareness*, and has become an aspect of particular concern to engineers and behavioural scientists involved in the development of complex human-machine systems.

While measures of performance and workload have been the typical metrics employed for determining the efficacy of human-machine interactions, there are certain conditions under which these measures are limited (see, for example, the work of Yeh and Wickens [1]). Take, for example, a situation in which the optimum strategy for an operator is to simply wait and monitor system variables before deciding whether or not to take action. In this situation there may be no overt performance to measure but cognitive load may be high. Further, consider a situation where an operator is flooded with activities, or the converse, where workload is relatively low and the operator is performing a passive monitoring role. Each of these scenarios, though arguably opposite in terms of their levels of workload, may produce a state of low situation awareness. In the former case the operator may have little spare capacity to develop a mental model while in the latter case the operator may be *out-of-the-loop* and lacking both relevant information, and a *feel* for the system dynamics which are essential to building the knowledge state that would allow an effective intervention. Because of the potential difficulty in determining operator effectiveness under these types of conditions, one might speculate that the concept of the mental model may help provide relevant information about an operator's *potential* to perform effectively in certain types of complex systems.

Therefore while workload, and situation awareness appear both to be relevant to human performance, their synthesis through theory has been sadly lacking. This paper outlines an attempt to build an integrating framework for *workload, situation awareness* and *performance* from two theoretical models, namely, Hendy, Liao and Milgram's [2] Information Processing (IP) Model and William T. Power's Perceptual Control

Theory or PCT [3]. A new construct, termed *cognitive compatibility*, will be interpreted within this framework. Brief mention will also be made of empirical investigations that have looked at the relationship between *workload* and *situation awareness* as measured by the NASA Task Load Index or TLX [4], and the Situational Awareness Rating Technique or SART [5].

3. WORKLOAD

3.1 The IP Model

In Miller's words (reprinted as [6]), "...Insofar as living organisms perform the functions of a communication system, they must obey the laws that govern all such systems..." Using an information processing paradigm, the IP Model attempts to provide a coherent theory for synthesizing much of the literature on workload and performance. The dependency of workload, performance and errors on *rate of processing*, is central to this model. For a more complete description of the IP Model, and the predictions that flow from it, see [2, 7, 8].

It can be shown from the IP Model, if the operator adopts a constant problem solving strategy, that workload and performance are both driven by the ratio:

$$\frac{\text{time taken to process the information necessary to make a decision}}{\text{time available before the decision has to be actioned}}.$$

This ratio provides a measure of the *time pressure*. The IP Model posits that performance, errors and subjective experiences of workload are all determined by *time pressure*.

The IP Model is a dynamic model, which predicts that an operator will adapt to excessive time load by two fundamental mechanisms, namely: (1) by reducing the amount of information to be processed; or (2) by increasing the time before the decision must be actioned. These mechanisms are attributed to changes in processing strategy, with such adaptations usually involving a trade-off between the amount of information processed and the achievement of an acceptable level of performance. Any particular problem solving strategy is assumed to involve certain processing structures at the neural level, with multiple *concurrent* tasks competing first for specific processing structures, and then for time [8]. A given structure is assumed to process in a time multiplexed serial fashion. It is assumed that the actual processing rate within a structure remains more or less constant [9], although the possibility that processing rate is affected by changing physiological states, brought on say by fatigue, is allowed.

While workload is generally regarded as multi-faceted, the IP Model reduces the effects of all factors that contribute to cognitive load either to their influence on the *amount of information to be processed* or to their effect on the *time allowable* before a decision has to be implemented.

3.2 The Relationship Between Workload and Performance

The IP model explicitly associates degraded performance either with the information directly shed if adaptation does not bring the time pressure below 1 or, alternatively, with the selection of a strategy that results in more rapid but less precise action (both situations involve information, which is relevant to the performance of the task, left unprocessed). Hence, performance and errors are inextricably and predictably tied to the imposed time pressure.

In the IP Model it is also assumed that operators respond to some function of time pressure when reporting subjective experiences of workload. With this assumption, a relationship between performance (defined specifically in the IP Model as the ratio between the *amount of information processed* to the *amount necessary for error free performance*) and operator workload is established through their common dependency on time pressure.

4. SITUATION AWARENESS

4.1 A Working Definition

In any activity, information is processed within the structure of the situation that the operator is immersed in. Knowledge of this situation gives context to the decisions that are made and gives form to the actions that are taken. In turn, this determines the appropriateness of the responses. Knowledge is resolved uncertainty. Hence, knowledge reduces the amount of information that must be processed in arriving at a future decision. This is the realm of Situation Awareness (SA). For the purposes of discussion, consider the following definitions:

The Mental Model is that part of the operator's internal state which contains the knowledge and structure necessary to perform a task. As such, the operator's mental model directly shapes the operator's actions and determines the potential to perform in accordance with the system demands. The mental model contains the operator's goal state and provides the reference against which actions are selected and initiated.

The term Situation Awareness (SA) particularly relates to that dynamic and transient state of the mental model which is produced by an ongoing process of information gathering and interpretation during the performance of some job of work. While the concept can be generalized to all tasks, no matter what their complexity, the term SA is usually used when considering tasks that have strategic and tactical components such as flying an aircraft, controlling or monitoring a plant, or tactical decision making.

These definitions emphasize the role that the mental model plays in shaping perception and action in goal-directed human activity.

4.2 Perceptual Control Theory

The role of feedback in goal-directed human activity, is a fundamental tenet of William T. Power's Perceptual Control Theory [3]. Powers' model is organized hierarchically with many goals providing the reference points for multiple layers of control; from the lowest levels of processing up to abstract goals such as the need for self esteem and actualization. In the PCT model, an action or behaviour is emitted in response to an error correcting signal that is transmitted with the intention of changing the state of the world so that the operator's perception matches a desired state or goal. The fundamental claim of PCT is that it is the perception that is controlled, **not** the behaviour. As behaviour is not the controlled quantity, one should expect considerable variability between and within individuals.

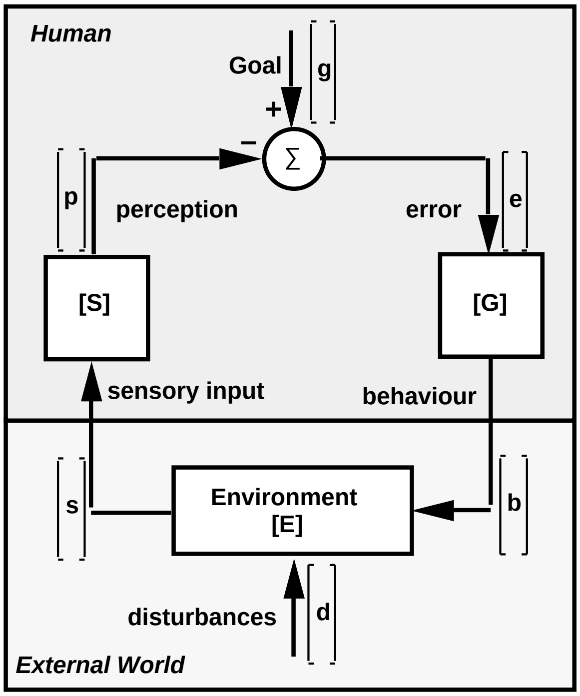

Figure 1. *William T. Power's Perceptual Control Model.*

Power's PCT model is represented diagramatically in Figure 1. The hierarchy of control is represented using a matrix formulation. The hierarchy of *goals*, *errors*, *behaviours*, *disturbances*, *sensory inputs* and *perceptions* are shown in vector form in Figure 1 (i.e., **g**, **e**, **b**, **d**, **s**, **p**), while the transfer functions **G**, **E** and **S** are shown as matrices. In general, **S** and **G** will have latencies or transport delays associated with the requirement to process information. These latencies have already been described in terms of the *decision time* in the IP Model. Transport delays effectively add an additional lag term to the loop which slows the rate at which the loop can respond to null an error state. The dynamics of the external world are contained in **E** (the characteristics of the vehicle or plant, the tactics of the opposing forces, the user interface, etc.).

From Figure 1, it can be seen that perceptions and actions are shaped by the transfer functions **S** and **G** as follows

$$\begin{bmatrix} e \end{bmatrix} = \begin{bmatrix} g \end{bmatrix} - \begin{bmatrix} p \end{bmatrix}$$

$$\begin{bmatrix} p \end{bmatrix} = \begin{bmatrix} & S & \end{bmatrix}\begin{bmatrix} s \end{bmatrix}$$

$$\begin{bmatrix} b \end{bmatrix} = \begin{bmatrix} & G & \end{bmatrix}\begin{bmatrix} e \end{bmatrix} \text{ and}$$

$$\begin{bmatrix} s \end{bmatrix} = \begin{bmatrix} & E_1 & \end{bmatrix}\begin{bmatrix} b \end{bmatrix} + \begin{bmatrix} & E_2 & \end{bmatrix}\begin{bmatrix} d \end{bmatrix}.$$

One can associate the goal state **g** and the transfer functions **S** and **G** with the operator's mental model. In fact if the set of all $\mathbf{g} = \{\mathbf{g}_1, \mathbf{g}_2, \ldots, \mathbf{g}_n\}$ represents all possible goal states, the combination of **S**, **G** and $\{\mathbf{g}_i\}$ could be considered to *be* the operator's mental model. It is expected that **S**, **G** and **g** will not be static but will change with time as learning and adaptation take place. The transfer matrices **S** and **G** contain all the transformation rules and relationships (the knowledge) that allows one to operate on the environment **E** in such a way that the perceived state of the external world can eventually be made to match the internal goal state. As the degrees of freedom for sensory input will be much greater than the degrees of freedom of the emitted behaviours, **S**, **G** and **E** will not be square.

4.3 The Relationship Between Situation Awareness, Performance and Workload

This interpretation of the mental model, in terms of a vector of goal states **g** and the transfer functions **S** and **G** of a multi-layered perceptual control loop, quite clearly illustrates the central role the mental model has in shaping both perception and action. The mental model contains stable long term memory relationships but also changes dynamically as the loop adapts to the transient aspects of the current situation. Note that this adaptation will only apply to those variables that are being actively controlled or attended to (the concept of *active control* does not require an overt action to be emitted as internal *imagination* loops are postulated). Hence, SA is gained over time through interaction with the environment (either *real* or *imagined*). Applying the IP Model to the transformation matrices **S** and **G**, one would argue that the transport delays experienced, in forming percepts from sensory inputs and in emitting actions from error states, will depend on the amount of information that has to be processed in going from **s** to **p** and from **e** to **b**.

Efficient and rapid processing implies appropriate strategies that involve small amounts of information to be processed (i.e., prior knowledge is used to reduce the uncertainty of the current situation, through the use of skill-based behaviours [10]; or Klein's recognition-primed decision making [11]). These strategies come from higher order knowledge, such as the relationships between things, and the integration of individual items into patterns. In a changing environment, the development of this knowledge is a task that demands attentional resources to service. Hence, SA and workload are obviously related to the extent that the development of these aspects of the mental model will depend on the availability of processing resources for the active control of these higher order loops.

In periods of overload, spare capacity may not be available to service these high level loops. Therefore while a high level of SA has the potential to reduce the amount of processing associated with some future decision, and hence reduce time pressure, it consumes processing capacity in the period leading up to that decision. When the workload comes from the control of loops that do not involve the variables associated with higher order SA, high workload will detract from the development of SA. Alternatively, if the workload involves the control of loops that involve the SA variables, high levels of workload may be associated with a well developed mental model. Hence, workload and SA are likely to dissociate.

4.4 Ramifications for Measurement

The definitions offered for SA in this paper suggest that an appropriate experimental paradigm for measurement would involve forcing a subject to make a decision, through some intervention, which is based on an understanding of the current state of some dynamic situation. This decision should be at the level of rule- or knowledge-based behaviour to be of interest. The key to this paradigm is the forcing of an action (performance) in order to test the operator's internal representation.

The manifestation of SA will be seen in the timeliness and appropriateness of the subject's decision(s) following the intervention (failure of an automatic system, retasking etc.). The word *appropriateness* rather than *correctness* is used here because a variety of actions can cause the error signal eventually to be nulled. All that is required, for effective and complete error correction, is that the loop gain be negative and >> 1. Other measurement techniques might include verbal protocols, or probes directed at eliciting the knowledge (the mental model) which is considered important to decision making (e.g., through the Situational Awareness General Assessment Technique — or SAGAT [12] — or similar methods).

Note that the timeliness of goal achievement depends both on the strategy used (as determined by the transformation terms selected from the transfer matrices **S** and **G**) and on the phase characteristics of the loop gain **SEG**. Actions that are *appropriate* will result in a high correlation (in the sense of zero phase error) between **p** and **g**. It is the role of training to develop an appropriate repertoire of primed perceptions $\mathbf{s} \rightarrow \mathbf{p}$ and actions $\mathbf{e} \rightarrow \mathbf{b}$. Therefore, while Powers suggests that the observation of behaviour is not a good indicator of goal-directed human activity [13], it seems that a range of normative and, in the sense discussed above, appropriate behaviours can be defined for many situations. Obviously this requires that goals have been clearly and unambiguously established.

5. COGNITIVE COMPATIBILITY

5.1 A Definition

Far less mature than the concepts of workload and situation awareness, the hypothetical construct of *cognitive compatibility* has been coined recently. Consider the definition [14]:

[The] Cognitive compatibility of advanced aircraft displays is the facilitation of goal achievement through the display of information in a manner which is consistent with internal mental processes and knowledge, in the widest sense, including sensation, perception, thinking, conceiving and reasoning.

5.2 The Relationship Between Cognitive Compatibility, Situation Awareness and Workload

The cognitive compatibility of a display can be interpreted in terms of the match between the characteristics of the display as represented by the sensory vector **s** and that part of the operator's mental model, contained in the matrix **S**, which operates on this sensory input. A cognitively compatible display would invoke only terms of **S** that result in the highest gain×bandwidth product possible. Thus, the *cognitive compatibility* of a display will be manifested in the time taken for goal achievement from the onset of some sensory input. From the IP Model, this translates directly into the timeliness and appropriateness of the emitted action(s).

This forges the link between cognitive compatibility and both workload (through the frequency domain) and the mental model (through **S**). Note that in observing behaviours, the effects of **g**, **G** and **E** are confounded with the effects of **S**. Hence, appropriate controls must be exercised in trying to separate the effects of cognitive compatibility from effects of changes in goals, strategy/response selection, or the external environment.

6. AN EMPIRICAL STUDY

An experiment was run to investigate the relationship between operator workload and situation awareness as measured by the NASA TLX and SART respectively. Of course such an experiment does not necessarily test the relationship between operator workload and SA, but merely investigates the relationship between two measurement instruments that are intended to capture aspects of these concepts.

6.1 The Task

The experimental task was a simulated Air Traffic Control environment. The task, called ATC 2.0, was an early version of a computer game which is available from the internet and various bulletin board services. Briefly ATC runs on a Macintosh computer and presents a simulated radar screen on which aircraft targets and the locations of airports are shown. The numbers of aircraft, airports and the session time are set by the experimenter. Aircraft arrive and depart at the 8 cardinal points of the compass as well as at airports. Flight paths (headings and altitudes) are controlled with a mouse using soft keys on the screen.

6.2 Subjects and Method

Ten subjects participated in the experiment. Sessions lasted 15 minutes. Twelve schedules were created with the number of aircraft arrivals ranging from 5 to 25. Arrivals at the eight cardinal points, and departures from airports, occurred randomly during the session time. At the termination of the 15 minute session the NASA TLX and the 10 dimensional SART [15] were administered.

6.3 Results and Discussion

The individual scale data from the TLX (6 scales) and the SART (10 scales) was subject to principal component analysis using SYSTAT version 5.2 for the Macintosh [16]. The resulting unrotated factor loadings are shown in TABLE 1. Factor loadings less than 0.5 are omitted for clarity. The first three factors together explain 69% of the variance. Varimax rotation spread the variance over more components but did not appear to yield a more interpretable structure.

The 16 scales in TABLE 1 were categorized according to their contribution to *Resource Demand, Resource Supply* or *Understanding* using the same taxonomy that Selcon and Taylor [15] used for SART. Lacking a theoretical rationale, this categorization is rather arbitrary. While the *Resource Demand* factors have some degree of face validity, the *Resource Supply* factors are more difficult to rationalize.

TABLE 1:

Unrotated factor loadings from the principal component analysis of the pooled TLX and SART scale data (factor loadings < 0.500 are omitted). The first three principal components (PC1, PC2, and PC3) are shown.

Scale	**Origin**	**PC1**	**PC2**	**PC3**
Resource Demand				
Mental Demand	TLX	0.917		
Physical Demand	TLX	0.517		-0.590
Temporal Demand	TLX	0.892		
Effort	TLX	0.912		
Instability	SART	0.662		
Complexity	SART	0.847		
Variability	SART	0.920		
Resource Supply				
Frustration	TLX	0.545	-0.577	
Performance	TLX	0.569	-0.534	
Arousal	SART		0.582	
Concentration	SART	0.857		
Division of Attention	SART		0.627	
Spare Capacity	SART	-0.765		
Understanding				
Quantity of Information	SART		0.738	
Quality of Information	SART		0.801	
Familiarity	SART			0.571

In many cases the distinction between a supply factor and a demand factor is ambiguous. Lacking a definition of a *resource* it is difficult to say what factors might result in their greater availablty.

In TABLE 1, the *Resource Supply* category is a mixture of emotional, global activating, and attentional factors. It is not clear for example whether subjects, in rating the scales, would see *Concentration*, *Division of*

Attention and *Spare Capacity* as driven directly by the task demands. If this were the case then this would place them on the *Demand* side rather than the *Supply* side of this taxonomy.

In terms of the IP Model, the resource that is being managed is time. Factors, such as *frustration, fatigue, mood, knowledge of one's own performance, arousal, motivation* etc. are claimed, in this model, to modulate the subject's efforts in adapting to increasing time pressure through the use of more time efficient strategies. From the IP Model, the role of attentional factors such as *Concentration* and *Division of Attention* in determining the supply of processing resources, is likely to be indirect.

It can be seen from TABLE 1 that the first principal component appears to be a demand factor. Although the *Spare Capacity* scale was originally categorized in the *Resource Supply* class, its loading on PC1 suggests that subjects were rating this scale in terms of (1 - *Demand*). Hence, this scale is perhaps more correctly thought of in terms of *Resource Demand* rather than *Resource Supply*. Similarly, subjects may have interpreted the requirement to concentrate as a manifestation of the task demands.

Factors associated with the *Quality* and *Quantity of Information* load most heavily on PC2. With *Concentration* and *Spare Capacity* shifted to the *Resource Demand* side, the remaining *Resource Supply* factors load partially along the directions of both PC1 and PC2. Therefore, in summary, two main factors emerge: (1) a demand or workload-related factor; and (2) a factor largely related to acquired knowledge (this could be termed the SA factor). It should be noted that the manipulation used in this experiment, and in the other experiments refered to in this paper, was mainly a workload manipulation. Not all factors of the TLX and SART scales were manipulated, either directly or indirectly, to create the variances necessary to fully identify the underlying structure of these instruments.

Overall the pattern of results from the ATC experiment is similar to that found by Selcon and Taylor [15]. One interpretation that may be offered for these results is that with the exception of the *Quality* and *Quantity of Information* scales (and possibly also the *Familiarity* scale) SART is largely a workload instrument. In the words of Selcon, Taylor and Koritsas [17] "*...It can be concluded...that both the TLX and SART are sensitive to changes in task demands, and that they appear, along this dimension, to measure the same things.*" They go further to draw the following conclusions "*...This could be taken as evidence that there is commonality, not just between the scales, but also between the concepts of workload and situational awareness.*" While the conclusion that SART and TLX instruments may measure much the same thing seems defensible, extrapolating to equate the concept of SA with workload does not appear to be justified. For this argument to be sustained it would have to be proved that TLX and SART are truly measuring what they purport to be, namely workload and SA respectively.

From the IP and PCT models, SA and workload can be seen as two independent aspects of human information processing. This theoretical position might be seen reflected in the pattern of weights from the first two principal components obtained both in the ATC experiment and in Selcon and Taylor's 1989 experiment. Yet despite this underlying independence, workload and SA are totally bound together albeit in a potentially predictable fashion.

6. DISCUSSION AND CONCLUSIONS

The combination of the IP Model and Perceptual Control Theory provides a coherent framework for tracing the relationships between concepts such as workload, situation awareness and cognitive compatibility. From this theoretical position one can talk about workload in terms of a readily understandable and measurable quantity termed *time pressure*.

Also emerging from this approach is the dominance of the mental model in shaping all goal-directed human activity. Rather than being a facilitator of action, there can be **no** action without the involvement of the mental model. Combining the IP Model with PCT, the relationship between workload and SA can be seen manifested in transport delays as sensation maps into perception and perceived error states are mapped into action. On the other side of this equation is the requirement for attentional capacity to be available so SA can be learnt in dynamic situations. Building the dynamic and transient knowledge associated with SA requires active control of the high level processing loops that use this knowledge for forming perceptions from sensory inputs and for shaping actions in response to perceived error states. In order to assess the state of this knowledge, these transformation rules and relationships must be made to operate, either by forcing an overt action or by knowledge elicitation techniques. Good SA is associated with rapid goal achievement through timely and appropriate actions in response to some sensory input. The mental model, in general, represents the organism's adaptation to the environment.

Cognitive compatibility is traced to the match between the sensory vector and the transformation relationships that form perceptions from this input. A high level of cognitive compatibility would facilitate goal achievement through timely and appropriately formed perceptions. Cognitive Compatibility is a property of the interface between the human and the environment, and represents an attempt to adapt the environment to be consistent with those terms of the organism's mental model that result in timely and appropriate actions. Therefore, cognitive compatibility has aspects of both consistency with the mental model and outright performance (in terms of a high gain×bandwidth product) associated with it. Both aspects must be satisfied for a display to be accepted as cognitively compatible.

Finally, because of the fundamentally separate and distinct nature of workload and situation awareness these two concepts should be treated and measured separately. However, because both workload and SA combine in their effects on task performance, attempting to validate metrics that are composites of workload and SA factors against performance is difficult. While it is workload, through time pressure, that ultimately determines performance and error rate according to the IP Model, the time domain behaviour of the perceptual control loops is entirely bound up in the state of the mental model. To summarise, in the simplest sense workload manipulations increase the rate at which decisions must be made while SA manipulations effect the timeliness of goal achievement.

7. ACKNOWLEDGMENTS

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