Utilising Cognitive Work Analysis for the Design and Evaluation of Command and Control User Interfaces

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***Abstract*—This paper reports on the design and evaluation of distributed net-centric command and control user interfaces for future air defence operations. The design was based on the Cognitive Work Analysis framework to identify the required capabilities and constraints in which the system would operate. The framework comprises of five phases that are populated using subject matter expert inputs. Each phase highlights a different facet of the work domain. Of particular interest is the final phase - Worker Competency Analysis - that is based on Rasmussen's human performance model. The model is used to capture the skills-, rules- and the knowledge-levels required by the operator. The author suggest that the model closely resembles the three levels of Situation Awareness - perception, comprehension and projection - and can be used to identify the measures with which to evaluate the developed user interface using Situation Awareness Evaluation techniques. The results are then used to scrutinise the conformance of the user interface design to its intended purpose.**

Keywords—Cognitive System Engineering, User Interface Design, Command and Control, Cognitive Work Analysis.

I. Introduction

Modern Command and Control (C2) systems not only demand information that is accurate, timely and relevant but also that the system should provide the necessary functional insight when confronted with unanticipated situations. Designing a user interface that caters for this is no trivial task. A thorough understanding of the work domain is required that encompasses tasks, strategies and worker competencies. In addition, the developed user interface needs to be evaluated to ensure that it conforms to its intended purpose.

The design discussed in this paper includes the development of two user interfaces (UIs) for C2 air defence operations. The first UI developed was for the Air Picture Manager (APM) who is responsible for maintaining an accurate air picture of a sectioned air space. The second UI was for Fire Control Officer (FCO) responsible for assigning engagement orders on hostile air targets. The operations performed by the APM is essential to support the FCO; the air picture is distributed over a net-centric infrastructure on which the FCO is connected.

Instead of re-iterating the functionality and usage of current systems, the design focuses on investigating alternative means to perform them. The design was intended to allow for a fresh perspective on how an APM and FCO can perform their role in the 21st century. The challenges faced were primarily to gain a thorough understanding of the air defence domain. This involved acquiring as well as translating the requirements into a representation that could be understood by designers, Subject Matter Experts (SMEs) as well as the stakeholders involved with the project. The second challenge faced was identifying what information is required for effective decision making in uncertain situations and how it should be presented to the operator. The third challenge was to identify the key aspects for evaluation the UI effectiveness as well the method of evaluation.

II. Cognitive Engineering Background

Cognitive engineering forms part of a field that is concerned with analysis, design and evaluation of complex sociotechnical systems. These types of systems refers to the interrelatedness between the socio- and technical-aspects present in the work environment. The field has evolved around a few key approaches from different research traditions and applied domains. These approaches include cognitive work analysis [10], cognitive task design [4], situation awareness-orientated design [3] and work-centered design [2].

The difference between these approaches lies predominately on the level at which the system is analysed as well as the cognitive areas on which they focus. Cognitive Work Analysis (CWA) focusses on identifying the high-level constraints of the design whilst cognitive tasks analysis lean more towards the lower-level requirements associated with performing tasks [7].

III. Cognitive Work Analysis Design

Any UI design starts off with implicit knowledge about the work it is intended to support [13]. Although intuition and common sense would suffice when designing rudimentary systems, explicit knowledge is paramount when it comes to more complex ones. For the prototype the design team decided to take a broad approach for the UI design. The team wanted to understand the air defence environment as a whole. This allowed to encompass a greater field of knowledge from which to spearhead further development.

CWA is a broad approach to system analysis. It consists of five phases with each subsequent phase building on the ones prior. The first phase essentially maps the environment from a functional perspective. It serves as the basis from which to identify the activities that control or drive the environment (done in the second phase). The result is an understanding of the ecological constraints in which the all important cognitive constraint can be investigated in the final three phases.

A. *Phase 1 - Work Domain Analysis*

The first phase of CWA is used to obtained a event-independent functional representation of the C2 work domain. It is used to identify and understand the domain's functional intent, as well as the necessary supporting functions to achieve it. Work Domain Analysis (WDA) breaks the C2 work domain down into five levels of abstraction that is presented hierarchically. The first level of abstraction represents the functional intent. Its description constrains the scope in which the domain operates. The second level represents the values, priorities and performance criteria to measure the progress of the subsequent levels towards the intent. The remaining three layers represent the required C2 functions, physical functions and the physical objects. Figure 1 shows a condensed version of the abstract-hierarchy developed for the APM-interface.

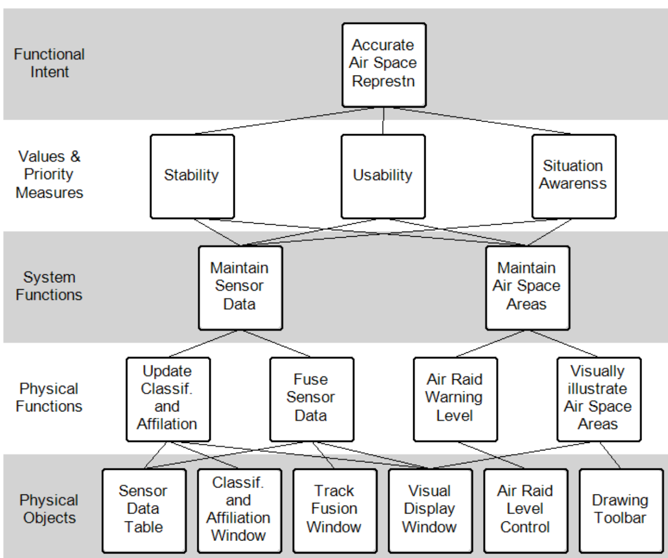

Fig. 1. APM's work domain Abstract-Hierarchy

The connection between the layers represents a means-to-end relation. Any given object's connection upwards refers to the reason of its existence. Connection downwards represents the means with which to realise the functionality. For example the physical function *update classification and affiliation* exists to realise part of the *maintain sensor data* overall C2 system functions. The means is supported by the physical objects *sensor data table*, *classification and affiliation window* and the *visual display window*. The representation also helps to identify the components that need to be in place to evaluate the design. The functionality of *maintain sensor data* can be evaluated independently from the *maintain air space areas*.

B. *Phase 2 - Control Task Analysis*

Where WDA identifies the functions needed to realise the C2 work domain's intent, Control Tasks Analysis (CTA) identifies the task requirements necessary to control them [13]. Information regarding the domain's state or situation is transformed by the control tasks into decision and procedures that drives to C2 work domain towards its intended goal.

TABLE I. CONTROL TASK QUESTIONS

Alert:	What notifies the operator of a new target.
Information:	What information is used to assess the target?
System State:	What situation can result from the assessment?
Options:	Depending on the situation, what are the available options?
Ultimate Goals:	What is the operator ultimately trying to achieve?
Target State:	What are the consequences of the decisions made?
Tasks:	What are the associated tasks that needs to be executed?
Procedures:	What confines the procedures that are executed?

CTA can be contrasted with normative and descriptive approaches to task analysis [8]. Normative techniques focus on how tasks *should* be performed, whilst descriptive techniques focus on how they *are* performed. CTA is a formative technique; it attempts to uncover the constraints in which tasks are typically performed. This allows designers to investigate alternative ways in which work task *could* be performed.

A Decision Ladder was used to engage with the SME on the tasks performed by the APM and FCO. The ladder was originally developed by Rasmussun whilst observing the work behaviour exhibited by experts in their field. It consists of a series of information-processing steps (boxes) that results in new knowledge-states (circles). It should be noted that the Decision Ladder is not a model used to derive the control task requirements directly [13], instead it serves as a template that maps the typical behaviour followed by workers in their work environment.

From the Decision Ladder, a set of questions relating to each of the functional activities identified in the WDA were developed. As an example, Table I lists the questions pertaining to the tasks performed by the *Update Classification and Affiliation* shown in Figure 1.

During the questioning process, operators found it easier to revert back to standard operating procedures (SoP) to explain the tasks performed. This behaviour was also noted by Naiker [8] since they are more comfortable explaining the work done in a descriptive manner. Although this is useful to understand the nature and characteristics of the work environment, it failed to clarify some of the lower level constraints imposed by the C2 work domain itself. Much of these constraints had to be assumed implicitly, but were later confirmed or corrected by discussing the operation with technicians.

The results were presented analogous to a black-box model: A description regarding the control tasks' context and purpose were stated, along with the required information and expected output when performing them. This was in accordance with the goal of CTA. The tasks are described in context to their constraints without focusing on the actual means to accomplish them. The actual means is investigated in the next phase.

C. *Phase 3 - Strategy Analysis*

Strategy analysis is used to identify the various alternative approaches taken by an actor in order to perform the control tasks. Where the analysis in the previous phase was used to identify *what* needs to be done, strategy analysis is used to investigate *how* these can be done [13]. There are various approaches to performing strategic analysis, some of which are more application and situation specific then others. An approach suggested by Ahlmstrom [1] offers a simplified approach used to investigate various approaches used to drive a system between a start-state and an end-state; the description of the activities between are characterised as being abstract or idealised representations.

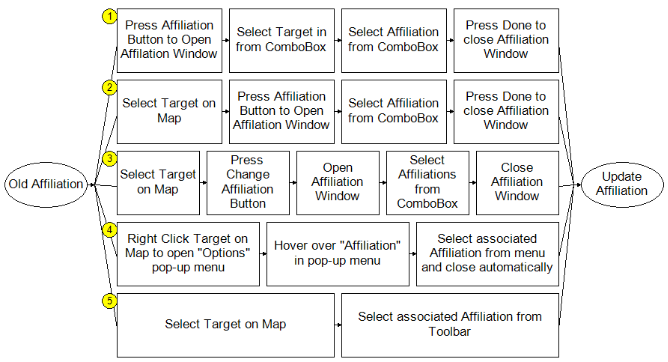

Fig. 2. Strategy Analysis for updating Affiliation

Figure 2 shows some of the approaches considered for the operator to update a target's affiliation. Each row represents a possible implementation that would allow the operator to perform a specific control task. The blocks represent a required task that needs to be performed. Although shorter tasks were preferred by the designers as well as the operators, the implementation was not always possible. Shortened tasks often required more information to be displayed on the screen placing a burden on the available screen real-estate.

Results from evaluating the UIs' usability indicated that operators preferred performing three steps or less. It is expected that future improvement and development will use this as a benchmark for the maximum number of steps required to perform a control task.

D. Phase 4 - Social Organisational and Cooperative Analysis

This phase investigates the how the tasks identified in the previous phases could potentially be distributed between the system's resources [5]. It is especially useful when dealing with large sociotechnical systems. The focus lies with the communication that takes place between the various entities and how this can be leveraged to enhance the overall performance of the work domain.

Apart from the air picture, the analysis identified very little additional information that needed to be communicated directly between the APM and FCO. It is expected that as the project evolves to include more aspects of air defence that this phase would become indispensable.

E. Phase 5 - Worker Competencies Analysis

The final phase of CWA involves identifying the competencies required by the worker in order to perform the expected functional tasks associated with the work domain. The analysis feeds from the conglomeration of information ascertained from the previous phases and is represented as an extension on the decision ladders identified in the CTA phase. Each processing activity and its corresponding state is analysed to identify the required skill-, rule- and knowledge-based behaviour.

Rasmussen [11] identified these behaviours as models of human performance in routine task environments and during unfamiliar task conditions. Skill-Based Behaviour (SBB) is represented by sensory-motor performance that takes place without conscious control. It is stimulated by the environment in the form of signals that have no real meaning other than representing information. This is analogous to when reading the value of a sensor gauge. A reading taken from a pressure gauge has no meaning apart from the actual value that it is pointing to.

Rule-Based Behaviour (RBB) is represented by responding to a sign from the environment in a way that was either taught or gained from past experience. Signs refer to states or situations; if the gauge reading enters into the red area a particular response is required such as opening a release valve.

In unfamiliar circumstances (when SBB and RBB fails) the required performance shifts to Knowledge-Based Behaviour (KBB) using symbols - the internal conceptualised functional understanding of the environment - to achieve a particular goal. Where signals and signs are externally referenced from the environment, symbols are part of the mental model associated with meaning. If opening the release valve has no effect on the pressure gauge reading, knowledge on the functional operation of the system would be needed in order to determine the cause of the problem.

A Worker Competency Analysis (WCA) was conducted on all the control tasks identified in the CTA. The analysis used the SRK Inventory proposed by Kilgore and St-Cyr [6] to map the skill-, rule- and knowledge-based performances to the associated control tasks. The SRK Inventory was then used to develop the set of questions that would be presented to the operators during evaluation to assess their SA.

IV. SOFTWARE DESIGN

Net-centric C2 in essence refers to interconnected units on the battlefield. This interconnectivity allows for information to be shared. For example, a unit equipped with a radar is tracking an enemy across the terrain. Since all the units are interconnected, the information can be relayed to another unit on the battlefield who now becomes aware of the threat. In addition the information can also be forwarded to the command centre who in turn can monitor the situation or deploy additional units.

The two enabling technologies of network-centric C2 is a robust communication medium such as fiber, wire or radio signals, and the actual information being distributed over the network. The type of information used in the design was predefined messages. These messages can represent an object, a unit, command, request and sensor data. The data fields found in each message describes the attributes associated with the message.

The advantages of using network-centric as opposed to platform-centric C2 are:

- A robust networked force improves information sharing.
- Information sharing enhances the quality of information and shared situation awareness.
- Shared information allows for collaboration and self-synchronization.
- It increases overall mission effectiveness.

Not only do all units have to be connected to some physical network, but they also need to share information between each other to realise a net-centric C2 environment. This is done using a publish-and-subscribe methodology where a unit subscribes to particular information flowing over the network. This approach is similar to subscribing to a magazine publisher. A subscriber selects the titles that they wish to receive over a period of time and they receive it when a new publication is made available. The subscriber also has the option to cancel a subscription if they no longer wish to receive it.

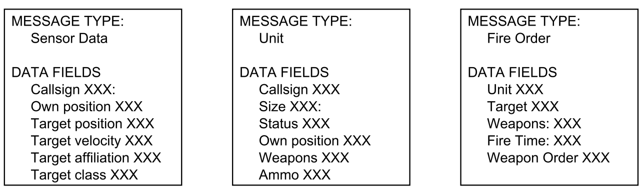

Fig. 3. Example of message types

In the design, the units subscribes to a message model where all the messages that are flowing over the network is stored. The messages model is synonymous to a database. Whenever a unit connects to the network, they receive all the latest messages that they have subscribed to.

The message model in turn is designed to subscribe to all information flowing over the network. This allows it to receive information from all other units connected to it. If a unit is equipped with a sensor and connected to the network, the messages from the sensor will be forwarded to the message model. The message model will in turn forward that data to all units subscribed to that message type. When a new unit connects and subscribes to the message model, all the current messages stored are forwarded to them. When new messages are added or updated in the message model, a copy is essentially made and forwarded to the unit.

The user interface utilises two types of technologies. The first is reusable graphical interface components known as widgets, and the second is a single 3D graphical display. A Widget contains elements such as sliders, text boxes, buttons and labels. It serves as a single point for direct manipulation of specific data (in this cause the messages being distributed over the network). The 3D graphical display enabled the geospatial representation of data on the battlefield.

A. Phase 1 - Work Domain Analysis

Functional analysis breaks down the C2 work domain into five levels of abstraction. The highest level being the work domain's overall intent, followed by the values, priorities and

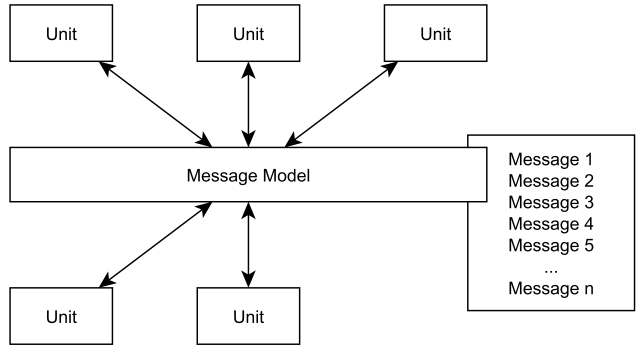

Fig. 4. Units connected to the distributed message model

measures used to qualify this intent. The third level identifies the required system functions, followed by the physical functions. The final level identifies the actual physical components present in the work domain. Each level is connected to the level below in a means-to-end relation.

For example the means in which the system function maintain *sensor data* is realised is through the *update classification and affiliation* and *fuse sensor data component functions*. These in turn are realised by the utilising the *sensor messages*, *system track override message* in the physical objects level.

The *component functions* were identified as representing the user interface widgets, and the *physical components* representing the messages flowing over the network. The abstraction hierarchy served as a means with which to identify all the widgets (and the associated messages) that would be required to realize the overarching system functions for the APM and FCO.

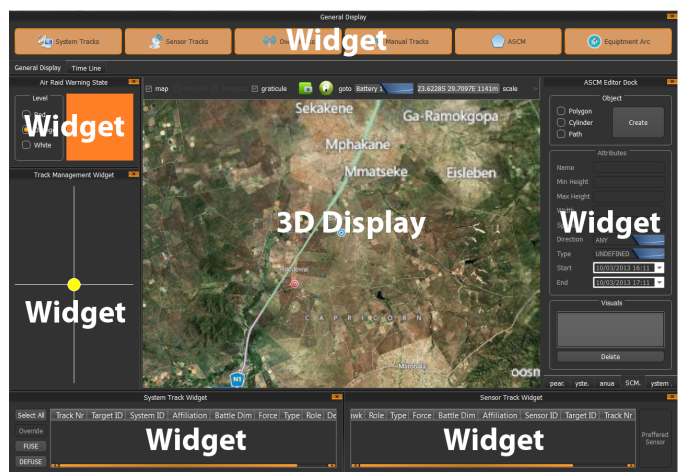

Fig. 5. User Interface utilizing widgets and 3D display

B. Phase 2 - Control Task Analysis

As the work domain analysis identifies the functional requirements of the system, the control task analysis identifies the task needed to control them. Information of the current state or situation is transformed by the task into decisions or procedures that need to take place in order to drive the system to its intended goal.

CTA makes use of a decision ladder. It consists of a series of states and processes. States are the current situation in the work environment, and processes are responsible for the transition between states.

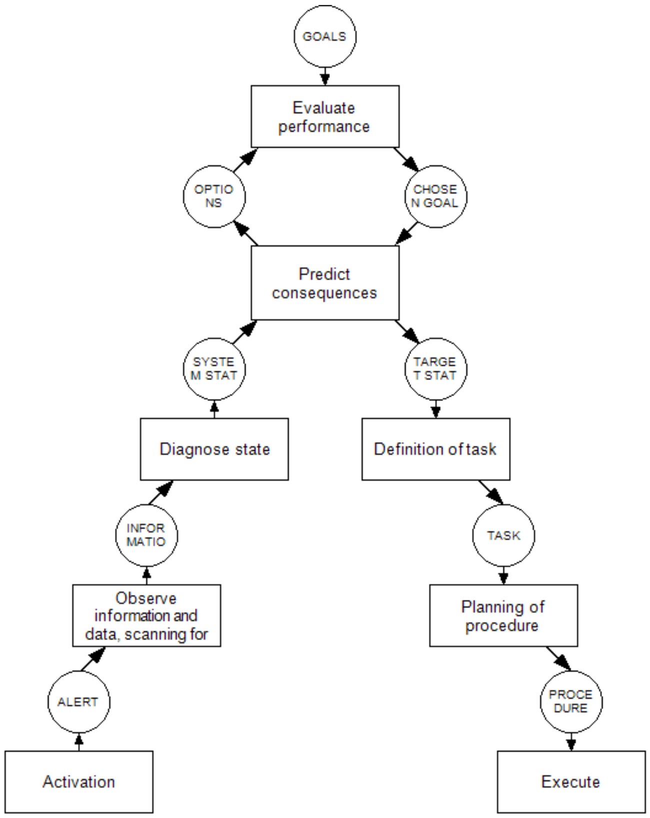

Fig. 6. Rasmussen's decision ladder

The decision ladder was used on the physical functions layer of the work domain analysis. A problem identified early with the utilisation of the decision ladder, was that its intended use is on operators that are already familiar with the states and processes in their work environment. Since the user interface was a new revolutionary design, no real prior knowledge on the exact utilisation of the user interface was available. Thus, most of the work done in this section was based on the knowledge from the SME and intuition from the design and development team.

By understanding what is meant by the various states and processes associated with the decision ladder, the researchers were able to intuitively deduce how the operator would typically perform their tasks. How would the user interface alert the operator that new information is present? How would the information need to be displayed? What information is used to deduce the state of the system? What would the available option be? What is the ultimate goal that they are trying to achieve? What target state would the information need to be driven? What are the tasks that need to be performed? What procedures are associated with those tasks?

Control task analysis identifies what tasks need to be done in order to meet the required physical functions of the design. The second challenged faced was how these tasks could be accomplished given the inherent constraints imposed by the technology used to develop the widgets and 3D graphics. This is where the utilisation of the strategic analysis phase aided in the design.

C. Phase 3 - Strategic Analysis

Strategic analysis is used to identify alternative approaches on how an operator can perform the control tasks. Although there may be numerous alternative approaches, it is important to keep in mind that they should be achievable within the selected technology's constraints used to implement the user interface. All technologies have inherent constraints, so it is important to be familiar with them before attempting this phase.

The strategic analysis focuses on the processes found in the decision analysis (refer to the blocks in Figure 6). For example, looking at the *Fuse sensor data* component found in the second level of the abstraction-hierarchy, the activation process can be accomplish in numerous ways.

When a sensor is tracking a new target, the new target would be displayed in the user interface's 3D display. How would the operator be alerted that there is a new target? One approach is to focus the view on the new target. But if multiple targets become available in a short period of time, then the view would be shifting between target, which would cause confusion. Another approach would be to only draw a pulsating circle around a new target. The circle would be removed once the operator has selected it. By selecting the target, information associated with it could be displayed in the widget.

D. Phase 4 - Social Organisational and Cooperative Analysis

Social organisation and cooperative analysis investigates how the tasks identified in the previous phases could potentially be distributed between the system's resources.

This stage identified how the same widget could be implemented on displays used by a different types of operator. For example, an Oversight Commander should have the ability to override a target that has been deemed hostile by the APM. In addition, the Oversight Commander should also have the ability to override an engagement that a FCO has given. Although a classification widget is not used by the FCO, and a Fire Control widget is not used by the APM, the Oversight Commander would be required to have access to both.

In short, the social organisational and cooperative analysis identified where widgets could be re-implement on different user interfaces.

E. Phase 5 - Worker Competency Analysis

The worker competencies analysis identifies the skills that an operator is required to have in order to perform their intended duties. The RBB, KBB and SBB was captured in a SRK inventory proposed by Kilgore and St-Cyr [6]. The information would typically be used to train operators on the operations of a given widget.

V. Design Evaluation

The system's Measure of Effectiveness (MoE) was identified during the first phase of CWA and is represented in the second layer of the abstraction-hierarchy in Figure 1 . Each of the three identified MoE were evaluated using different techniques. UIs' stability was evaluated using load-testing but is not discuss as it falls outside the scope of this paper. The overall usability of the UI was evaluated using subjective feedback from the users obtained with questionnaires; the evaluation used Heuristic Analysis developed by Nielsen et al [9]. Finally, the user's Situational Awareness (SA) was assessed using the Situational Awareness Global Assessment Technique (SAGAT).

A. Evaluating Situation Awareness

Endsley et al [3] defines SA as being aware of what is happening around you and understanding what that information means to you now and in the future, and only those information that are relevant to the task at hand are important to situational awareness. There are three defined levels of situational awareness: perception, comprehension and projection. The researchers argue that the three models of human performance proposed by Rasmussen closely resemble the three levels of SA described by Endsley et al.

Both SBB and SA-Perception refers to sensory stimuli as the means with which to obtain information from the environment. The meaning of the information in both approaches is not the main concern but rather the value or status of the information. RBB and SA-Comprehension do however focus on interpreting the meaning of the information. Here the information is synthesised and compared to either rules that needs to be followed (RBB) or objectives that needs to be realized (SA-Comprehension). Finally, both KBB and SA-Projection requires an operator to have a good understanding of the functional properties of the environment. This helps to maintain the conceptualised mental model needed to perform tasks require for forward-thinking. It is because of this close resemblance between the two approaches that the skill-, rule- and knowledge-based behaviours (identified in the WCA) to derive the questions used in the our Situation Awareness Global Assessment Techique (SAGAT).

Data for the UI was generated in real time using a Simulated Environment (SE) developed by the CSIR and industry. The SE uses configurable sensor-, weapons- and aircraft-models to create hypothetical battlefield scenarios. Participants were first introduced to simple scenarios to familiarise themselves with the UI's operation. After this, they were divided into teams of two to operate the APM- and FCO-interface. The evaluation scenario was designed to capture all the identified competencies. The scenario was paused at particular stages in the scenario to present the participants with a few questions relating to the current situation found on the battlefield. The questions were presented over the UI blocking it from view. Only after answering all the questions could the participants return to the UI. The scenario was unpaused once both participants had submitted their results. The results were stored on a disk and collected after the evaluation.

Although the FCO depends on the APM to provide the air picture from which to perform engagements, the FCO was not penalised for incorrectly responding to questions relating to the air picture. If for example to APM incorrectly marked a hostile target as a neutral, the evaluation on FCO was based on what was presented.

B. Evaluating Usability

A questionnaire regarding the usability of the design was presented to the participants after completing the final scenario. The evaluation was based on Heuristic Analysis [9] and it was decided to focus primarily on visibility, efficiency and accuracy. Visibility referred to the ease with which the function's associated data and controls could be found. The options were [a] Knew where everything was, [b] Had to search sometimes, or [c] always searched around. Efficiency referred to the time it took to complete a function which could be either [a] quick, or [b] too long. Accuracy referred to the number of perceived mistakes made whilst performing the functions. The options were [a] No mistakes, [b] Some mistakes, or [c] A lot of mistakes.

C. Results and Discussion

The overall SA of the AMP and FCO is presented in Figure 7. The FCO *($M = 82.84$, $SD = 4.99$)* performed slightly better than the APM *($M = 76.92$, $SD = 6.93$)*. The FCOs were evaluated on the actual air-picture presented by the APM. Initial data evaluated showed a strong correlation between the SA of the FCO and the APM. The results suggested that the FCO and the APM exhibited the same level of SA. On closer inspection it was determined that this correlation was due to the fact that some of the questions presented to the APM were similar to those presented to the FCO. The APM was penalised for incorrectly affiliating a target. The incorrect target was however displayed on the FCO user interface; when questioned, the FCO would answer a question based on what they perceived. Unfortunately a correct answer by the FCO was marked as incorrect by no fault of their own. This could fortunately be corrected after the process since each scenario was recorded by the SE.

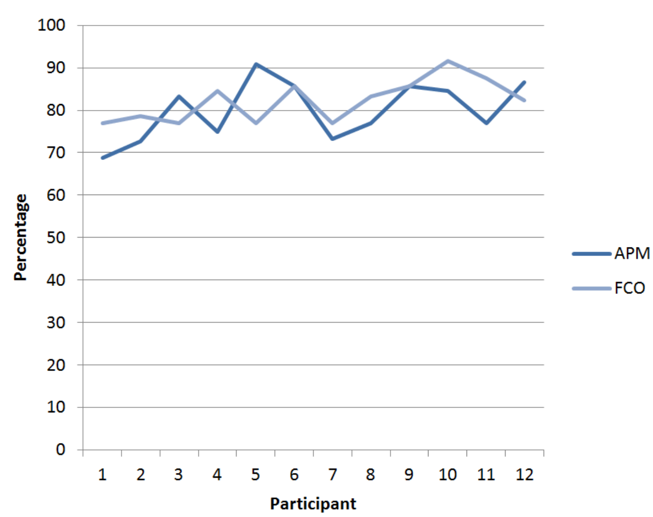

Fig. 7. Overall Situation Awareness of APM & FCO

Specific questions relating to level 0, 1 and 2 SA are presented in Figure 8. Since the questions were obtained from the CWA itself, identifying critical areas could be traced back from the WCA (final phase) through to the WDA (initial phase).

The usability analysis provided subjective feedback from the operators. The results suggested that the areas that scored low on the SA were also the functions that proved to be the most difficult to use. Reviewing the strategic analysis approaches taken, it was found that the functions that required more than four steps to perform were regarded less useful than those that could be done in three steps or less. This provided a benchmark that could be used to redesign some functional components accordingly to improve on the overall usability.

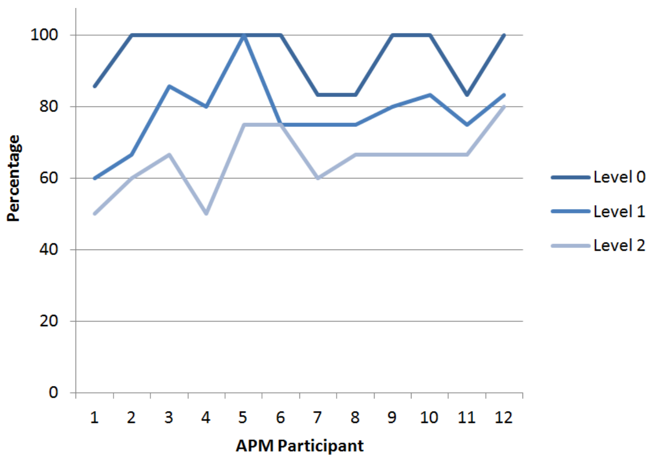

Fig. 8. Levels of Situation Awareness for APM

VI. Conclusion

The work described in this paper was the design and evaluation of C2 UIs using the CWA framework expected to have a high level of usability and ensure that the operator could maintain a high level of SA.

One of the benefits of using the CWA framework is that it allows the C2 work domain to be captured from a holistic perspective where the designs overall measures of effectiveness is stated. The advantage of using this is that it defines the scope of where the design focus lies. Each subsequent phase builds on the initial description providing more detail on how the design can be achieved.

The inherent traceability offered by the framework allowed for unsatisfactory results to be re-evaluated from the cognitive performance back to the functional intent. This allows for greater understanding of the effect that certain design changes would have throughout the C2 work domain.

Acknowledgement

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