A Work-Centred Approach to Seeding the Development of Design Concepts to Support Shipboard Command and Control

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Abstract

We present results from an ongoing investigation using a work-centred framework to design computer-based tools to support the cognitive and collaborative work of Command Teams on a HALIFAX Class frigate. Based on emerging concepts in Cognitive Systems Engineering, the design approach hinges on analyzing the operators' work demands and finding ways to use technology to improve the performance of the joint cognitive system of operators and their aids. Specifically, we describe our use of two work-modeling tools within the framework that contribute to developing a traceable design thread, directly linking knowledge elicitation and work analysis outputs to specific design hypotheses for supporting the work demands of Command and Control operators. The two tools are drawn from Rasmussen and Vicente's Cognitive Work Analysis framework. The first is an Abstraction-Decomposition Space. It uses an Abstraction Hierarchy to describe how the functional purposes of the work domain are achieved. There is also a Part-Whole Hierarchy that decomposes the work domain into components that contribute to achieving those purposes. The second tool is a set of decision ladders representing the information processing and knowledge states of operators in conducting control tasks. We also briefly illustrate one interface concept that was derived with the approach.

1. **Introduction**

Defence R&D Canada - Atlantic is investigating technologies such as data fusion and advanced operator-machine interfaces to support naval operators in the Operations Room of a HALIFAX Class frigate in their Command and Control (C2) work, focusing specifically on their work areas of maritime tactical picture compilation (MTPC) [1] and tactical planning and response management (TPRM) [2]. The tactical picture, compiled from Above Water Warfare, Underwater Warfare, Tactical Data Link and Wide Area Picture data inputs, is the situation picture underlying all aspects of Command and Control decision making over an area of interest of a maritime commander. Tactical planning and response management is concerned with the development, integration and management of tactical plans within and across the air, surface and subsurface warfare areas.

A key aspect of this investigation is determining the requirements for effective computer-based tools for MTPC and TPRM. The research literature on existing complex sociotechnical work environments that share many of the characteristics of C2 provides strong evidence for the merit of designing cognitive and collaborative support systems for such environments based on an in-depth understanding of the work system and the specific work demands that operators have to deal with (e.g., [3]). In such a design approach, some form of work analysis to model the operators' work demands posed by the work environment inevitably emerges as a critical consideration. We have been investigating such an approach for the HALIFAX Class frigate. It is based on emerging concepts in the field of Cognitive Systems Engineering [3].

In this paper, we review our design framework and describe how two work-modeling tools have been used within the framework to identify work demands of C2 operators on a HALIFAX Class frigate and uncover potential design solutions to support these demands. A significant and novel contribution of the approach is that it permits developing a traceable design thread that directly links knowledge elicitation and work analysis outputs to specific design hypotheses for supporting operator work demands. Finally, we briefly illustrate one tentative interface concept for supporting tactical picture compilation work on the frigate that was derived with the approach.

2. Exploratory design framework

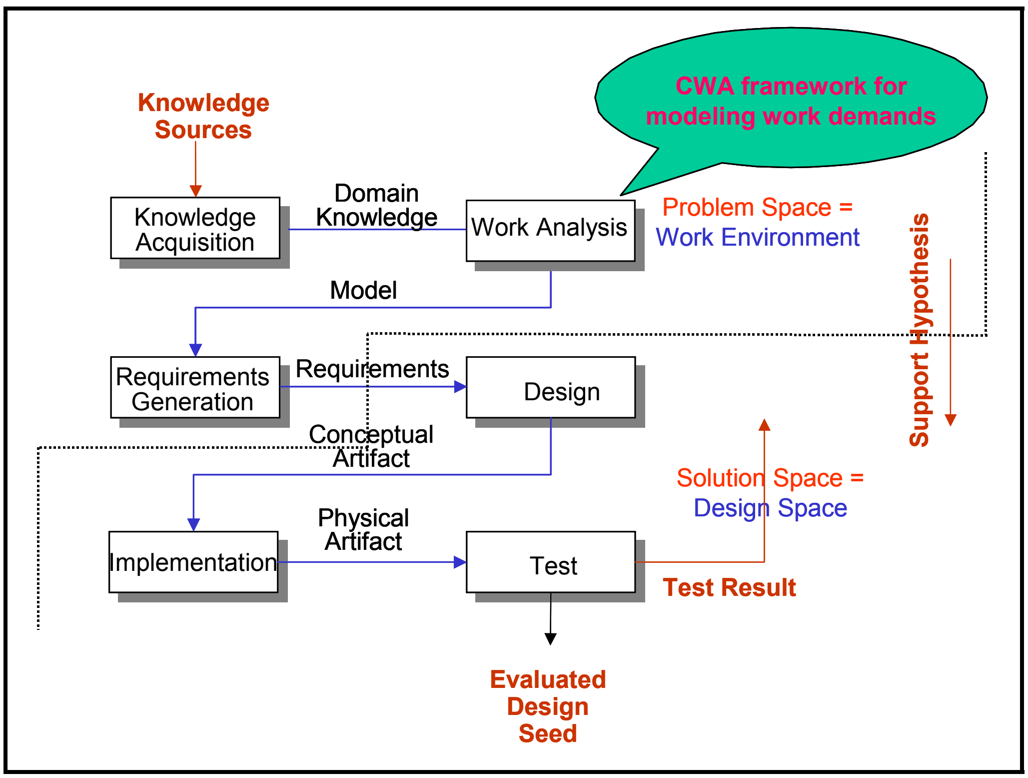

Figure 1. Methodological framework for eliciting design seeds

The primary purpose of our exploratory design framework is to permit developing and testing, from a work-centred perspective, design hypotheses for supporting operators with advanced computer-based capabilities in their individual or collaborative cognitive work. We review its principal elements. Additional details can be found in [1]. The framework encompasses various activities aimed at developing an increasing understanding of the work's demands, and using this to develop and test specific hypotheses about ways to support operators with these demands. Figure 1 illustrates the framework, showing, for concreteness, one specific activity trajectory within it, and the activity nodes on that trajectory and their potential linkages in terms of inputs and outputs. In practice, however, design involves continuously shifting focus in a nonlinear manner among the activities in Fig. 1, between the problem space (the work environment) and the solution space (the design space), according to a hypothesize-and-test design paradigm.

An essential part of the framework is a work analysis that explicitly models work demands or constraints in the work environment as a basis for design. This explains why we refer to the approach as work-centred. Analysis is therefore a work-modeling process, providing a critical link between knowledge acquisition and design activities. This analysis is conducted along the lines of Rasmussen and Vicente's Cognitive Work Analysis (CWA) framework [3]. CWA is a systems-oriented approach to analyzing a work environment aimed at capturing the behaviour-shaping constraints for that environment. Such constraints delimit an envelope within which all productive work occurs. This underlies the formative focus that CWA brings to design, by providing a modeling capability to deal with demands across a broad spectrum of situations, from familiar ones that operators encounter routinely, to unfamiliar, but anticipated ones (i.e., anticipated by system designers, policy, doctrine, tactics, and procedures), to ones that are unfamiliar and unanticipated.

Hypotheses for supporting work are rendered as design seeds, each seed effectively instantiating some specific support hypothesis that needs to be tested[1]. Figuratively, work analysis serves to 'seed' promising design concepts that may turn into design 'nuggets', which when integrated could be used in defining a complete capability for supporting work demands. Testing the validity of a support hypothesis for a seed might range from obtaining initial subjective Subject Matter Expert (SME) feedback to the seed to conducting objective performance tests with it. In this manner, therefore, complex aspects of the work's demands are decomposed into manageable portions for design purposes. In addition, increasingly realistic prototypes of design seeds can be iteratively developed, refined, integrated, and tested, leading eventually to a coherent support capability.

We have used a variety of approaches in our work to date to do the knowledge elicitation with SMEs to produce domain knowledge needed for the CWA modeling shown in Fig. 1. In one approach, described in [1], a detailed paper-based description of a tactical scenario was first prepared. Teams of operators were then walked through a series of static screen configurations presenting the state of the tactical situation confronting the frigate at various times while they described their own and their team's activities, in terms of their goals, information needs, information sources, information transfers, processing activities, strategies, and the collaboration that might be involved. Concerns with this approach stemmed largely from its inability to capture the rich detail and dynamic, contextual nature of C2 work on the frigate.

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[1] Referring to these instantiations as design seeds is meant to capture their essential role as one of seeding or jumpstarting an exploratory design process. The terminology is borrowed from Patterson et al. [4]. A seed represents some specific and relatively independent support concept for some specific aspect of the work. In our work, we have focused on seeds of a computer-based nature. A particular seed could be realized in a number of forms, from a very crude, static mock-up to some sort of working prototype.

In subsequent work, we adopted a detailed scenario-based approach [5]. Significant effort was expended to work with an SME to first build a complex, tactical scenario comprised of a variety of challenging work situations set in a realistic mission context. This was then programmed and run in a Canadian Navy trainer with a portion of the Operations Room operators working as they would normally in response to the unfolding events in the scenario. Data was collected during scenario runs, at pauses during intervals when the scenario was frozen, and then at the end of a run in a debrief session. While this approach remedied some of the deficiencies of the previous paper-based method, it also exposed some critical data collection deficiencies in the trainer.

Recent knowledge elicitation has focused on adapting Klein's Critical Decision Method (CDM) [6]. This change stemmed from a concern that by presenting SMEs with a scenario, it restricted the breadth of information that could be collected. This would mean that any support concept eventually developed would address a 'layperson's' understanding of what the naval operator does, rather than the SME's. Because the layperson cannot have the SME's breadth of domain experience and understanding, issues identified and their associated support concepts might not address the more critical operator work demands. To overcome this in scenario-based data collection approaches, an 'open' approach to data collection (CDM) was therefore adopted.

CDM has permitted SMEs to describe what they considered to be the most difficult situations they encountered. Once the problem space was bounded in this way, analysts could systematically investigate each facet of the problem space. This approach provided the data to construct a detailed account of the actions the operators would undertake in the scenario they described, including the triggers, information requirements and outputs. Using this approach, it is felt that the resulting support concepts will be more relevant and acceptable to operators.

It is unlikely that any one knowledge elicitation approach will provide all the data needed to conduct a complete CWA. Multiple techniques may be needed, tailored to the specific types of demands being modeled or the specific design questions being considered, or simply to produce a converging picture of those demands. There will also be a variety of pragmatic constraints such as the availability of SMEs, the time that can reasonably be devoted to data collection, the cost and overhead involved, and so on, that enter into the choice of method(s). Further research is needed to improve our understanding of the large variety of considerations involved and the various approaches that could be productively employed in conducting a CWA.

3. **Work modeling**

In this section and the next, we discuss how we have been using the previously described design framework to elicit design seeds according to the design activities: develop work models → develop design seeds and their associated support hypotheses. We concentrate on the specific process employed in recent work to elicit design seeds for TPRM, where a variant of the CDM was used with three teams of operators over a period of 1.5 days in the Knowledge Acquisition activity in Fig. 1.

The current section focuses specifically on the development of the work models from the CDM data. Two types of work models have been developed by a team of four analysts: a Work Domain Analysis (WDA) and a Control Task Analysis (CTA). Both are steps in a CWA [3]. A WDA identifies the functional and part-whole structure of the work domain. A CTA identifies what needs to be done in effecting control tasks in the work domain.

3.1 WDA modeling

A WDA models a work domain in the form of an Abstraction-Decomposition Space (ADS), displayed as a matrix. Along the vertical axis of the matrix are the various abstraction levels for the work domain (its Abstraction Hierarchy). Along the horizontal axis is a Part-Whole Decomposition of the domain corresponding to its different levels of resolution.

Five levels of abstraction were used. These are shown in Table 1, along with the generic questions each level provides answers to for the domain [7]. Based on SME statements collected in the CDM, analysts developed a list of decomposition levels that were referred to and which were therefore involved in some way in the work of the Operations Room team. Seven levels of Part-Whole Decomposition were thereby established, and descriptions of what each level encompassed were created. These levels and their descriptions are shown in Table 2.

Abstraction Hierarchy Level	Generic Questions
Functional Purpose	What was the work domain designed to do?
Abstract Function	What are its underlying laws or principles?
Generalized Function	What are the processes that are involved?
Physical Function	What entities are involved and what are their capabilities?
Physical Form	What is the physical appearance and location of an entity?

Table 1. Levels in the Abstraction Hierarchy

World	*Operational Environment*	*Local Environment*	*System*	*Sub-system*	*Component*	*Sub-Component*
Geopolitical, weather, geophysical, etc.	Physical (including air, surface and subsurface contacts - both hostile and friendly (Task Group)) and non-physical (air/ship lanes, weather) elements	Logical groupings within operational environment (e.g., Task Group, Air Contacts, Environment)	Self-contained units within the operational environment (e.g., Own-Ship)	Logical groupings within self-contained units (e.g., personnel, vehicles, ship systems)	Entities within logical groupings of self-contained unit (e.g., information system, communication system, bridge personnel, helicopter, weapons systems)	Component elements of entities (e.g., a weapon, an element of database, information, rudder)

Table 2. Part-whole decomposition

Once the ADS matrix was created, each SME statement was mapped independently by each analyst to a specific cell in the ADS. A set of exemplars was also produced for each cell of the ADS. An exemplar is a particular example of a type or category of a member of the cell. For example, “Meet Naval Values” was an exemplar for the Functional Purpose of the System (comprising OwnShip). A starting point for the exemplars was earlier work to develop an Abstraction Hierarchy for the frigate [8]. Exemplars provided a consistency check for analysts to individually determine whether their mapping of SME statements to ADS cells was appropriate. Analysts also met at the end to discuss their analysis and agree upon a final mapping. If any clarification was needed for a particular statement, its wording was changed to reflect the analysts' interpretations. During these discussions, additional mapping rules were also discussed and clarified as needed. This mapping onto the ADS explicitly exposed how SMEs traversed the different levels of abstraction and decomposition of the work domain over the course of the scenario developed during the CDM interviews.

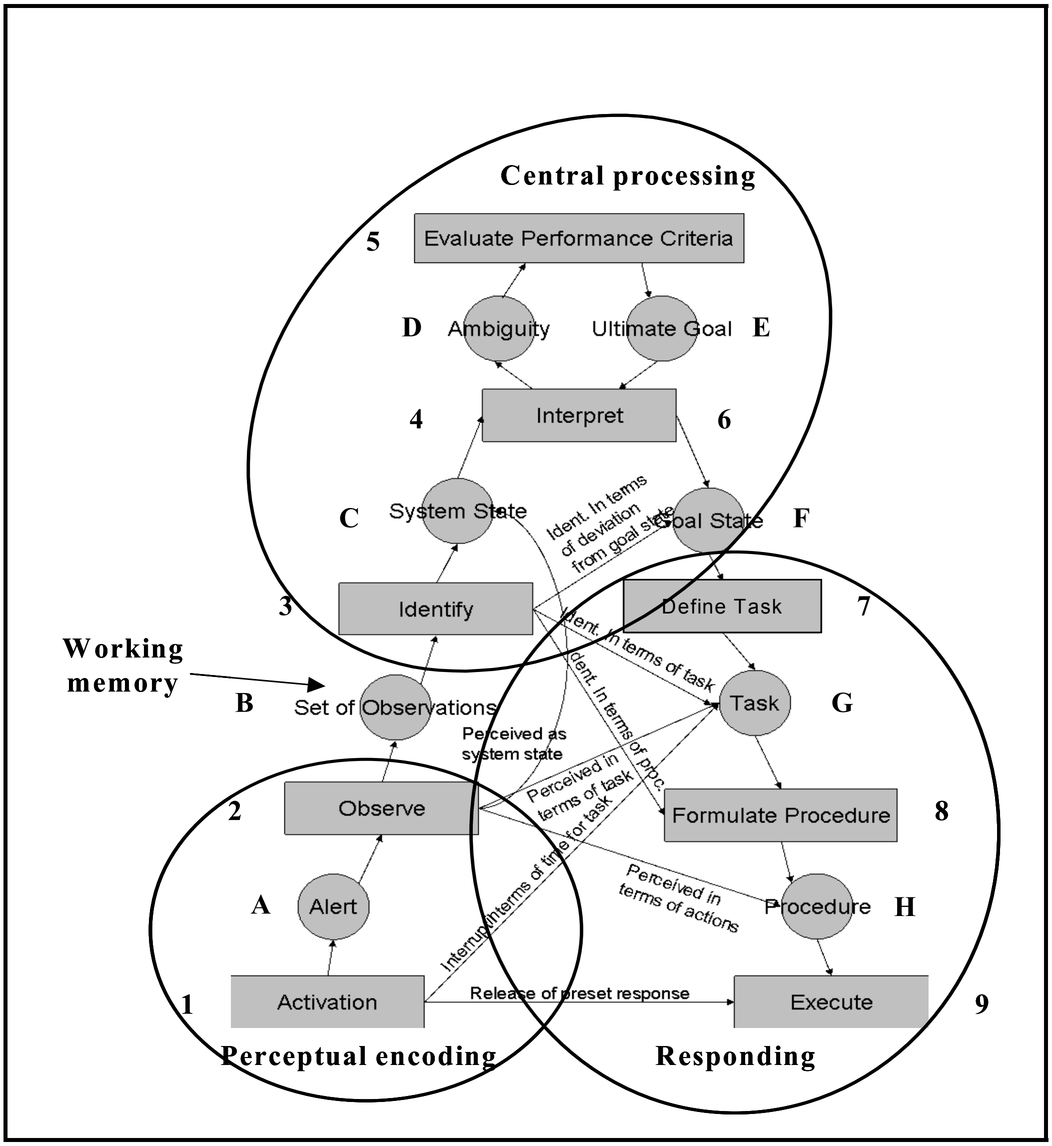

Figure 2. Decision Ladder template, coding scheme, and stages of human information processing

For a concrete example of the mapping process, consider the SME statement: "Determine trade-off to defend them and put self at undue risk (i.e., sacrifice OwnShip to protect a High Value Unit (HVU))". In this statement, 'them' refers to the HVU under escort. This statement impacts both the frigate and the HVU. The decomposition level must therefore be above the System level, i.e., Local Environment or Operational Environment. Since the HVU was part of the Task Group, this statement was placed at the Local Environment level. Balancing the risks involved in tactical plans concerns the underlying laws or principles governing operator action. There is no definite process governing this activity. Therefore, this statement was placed at the Abstract Function level.

3.2 CTA modeling

A CTA maps out data-processing activities and states of knowledge in a control task, from activation to execution, in the form of a 'Decision Ladder' template. The ladder, shown in Figure 2, has been 'folded' to reinforce the notion that an operator can take efficient processing 'shortcuts' in a particular task by 'leaping' or 'shunting' between non-sequential points in the ladder, thereby bypassing intervening information-processing steps. Boxes correspond to data-processing activities and circles to states of knowledge.

Decision Ladder Step	***Vicente [3]***	***Analysts' Additional Interpretations***
Activation	Detection of need for action	Perception
Alert	What's going on?	Realisation
Observe	Information and data	Display of contacts and other information
Set of Observations	What lies behind?	A body of information
Identify	Present state of the system	Consider the information
System State	What's the effect?	What does this mean?
Interpret	Consequences for current task, safety, efficiency, etc.	How does this fit into the perceived 'idealised' progress toward the goal?
Ambiguity	Which goal to choose?	It's unclear how it fits
Evaluate Performance Criteria		How should it fit?
Ultimate Goal	Which is then the goal state?	This has this effect on the ultimate goal
Interpret	Consequences for current task, safety, efficiency, etc.	What steps need to be added to get progress back on track?
Goal State	Which is the appropriate change in operating conditions?	Know what needs to be achieved
Define Task	Select appropriate change of system conditions	Determine what need to be done
Task	How to do it?	Know what needs to be done
Formulate Procedure	Plan sequence of actions	Plan how to do it
Procedure		Know how to do it
Execute	Coordinate manipulations	Do it

Table 3: Steps in Decision Ladder, with additional clarification

To simplify the analysis of SME scenario data, a coding system for the Decision Ladder was adopted in which states of knowledge corresponded to letters and data-processing activities corresponded to numbers (see Fig. 2, showing the codes next to the boxes and circles). The 'Interpret' activity was coded twice (4 and 6) to distinguish whether the operator is interpreting the consequences of the 'Ultimate Goal' or interpreting the consequences of the 'System State'. Coding each step allowed tracking where a particular decision-making sequence entered the ladder, how it moved through the ladder, and where it left the ladder. The coding structure also permitted easily recognizing leaps and shunts in a particular decision-making sequence. Shunts correspond to a number followed by a non-sequential letter sequence, and leaps to two consecutive letters.

After outlining the coding structure, further definition of each step was agreed upon by all analysts. This ensured that analysts had a consistent interpretation of the different steps. Table 3 outlines these definitions. Each analyst then independently analyzed every task outlined by the SMEs. Letters and numbers were assigned in order, mapping the steps involved in the task onto the ladder. As in the WDA modeling, analysts met at the end to discuss and reconcile the analysis of each and every statement and to agree upon a final mapping.

To concretely illustrate this mapping process, consider again the SME statement that was previously mapped into the (Abstract Function, Local Environment) cell of the ADS matrix: "Determine trade-off to defend them and put self at undue risk". In the CTA, this was mapped onto the sequence 4D5E6 in the Decision Ladder. Considering the task, the operator (in this case the ship's tactical coordinator) must already have a set of observations and know the system state; he is now using this information to "determine trade-off…". The operator is interpreting the information he has, hence '4'. However, because he is determining trade-offs, we can assume that there will be some ambiguity, an assumption supported by the rest of the statement "…to defend them and put self at undue risk…". This takes the operator to the 'D' state of knowledge. The operator must then evaluate the performance criteria, not only for the frigate (e.g., can I realistically defend myself if we are actually attacked? What is the likelihood of attack?), but also for the mission (e.g., do I really have to defend this other vessel? What are my orders?). This leads to an altered ultimate goal, meaning he has passed through '5' on his way to 'E'. The operator is left considering what this new, altered ultimate goal means for the current task, which is '6' in the analysis.

4. **The process of developing design seeds and associated support hypotheses**

In Section 3, we described how we mapped SME statements obtained by the CDM into the Abstraction-Decomposition and Decision Ladder templates of a WDA and a CTA, respectively. The work models developed in this manner provide the basis in our approach for considering what is uncovered in terms of design seeds.

A design seed is accompanied by a hypothesis, often implicit, regarding the nature of the support it affords. For instance, a seed that suggested the need for a flashing alert to cue operators' attention would carry with it a support hypothesis like: the operator will more quickly notice a contact in the presence of the alert than without it.

We found it useful to base the development of design seeds on a combined set of considerations. Collectively, these considerations can be viewed as stages in an analysis process that build on each other. This process starts with an initial determination of a generic, coarse set of design seed themes based on purely cognitive considerations, and converges toward a set of specific design seeds and their associated support hypotheses based on including consideration of the results of the WDA and CTA modeling. Four stages were involved in the process.

1. Identify potential difficulties for the operator on the basis of the SME statements collected.
2. Map the cognitive basis of those difficulties.
3. Analyze the WDA modeling results.
4. Analyze the CTA modeling results.

Element of Cognition	Design Seed Theme	Support Hypotheses
Mental models	Specific display entity (present the stimulus that is the 'organizing principle' for a mental model and thus immediately trigger that entire mental model, rendering it available for problem solving and decision making or action). This display entity must be based on a good understanding of the organization of information in long-term memory	Operators will be able to infer more about a situation from a single display object
Attentional resources	Minimization of workload, better distribution of tasks across different channels, reduction in need for complex mental calculations, possibly through reducing the demand on working memory, by creating external representations of information that would otherwise need to be stored in working memory to be used in the calculation	Operator activities will be more accurate and complete
Decision making	Presentation of information in a form that can be readily used; system-generated 'starting points' to kick start the operator's decision making or allow them to focus on complicating factors. This includes the explicit display of emergent properties in a representational aid	Operators will exhibit more efficient and accurate decision making, as measured from the conscious receipt of new information to execution of some activity
Working memory	Data fusion; externalization of information that would otherwise need to be held in working memory	Operators will have more spare working memory capacity
Situation awareness	Presentation of overview information with the opportunity to drill down for more detailed information; suitable for command role, all the way down to individual operators	Operator will exhibit better situation awareness
Communication	Large shared display, integration of systems, re-location of some systems	Operators will engage in more accurate communication
Collaboration	Large shared display, graphical forms of communication	Operators will work more efficiently together to develop solutions

Table 4. Mapping elements of cognition to design seed themes and associated support hypotheses

The contribution of each of these stages to the process is discussed in more detail below. The first two stages listed above allowed identifying general design themes from SME statements, and provided the basis of their cognitive justifications. By comparison, the last two stages produced more specific design information (e.g., specific support requirements, nature of support to be provided, operator interactions). This process led to an extensive set of specific design seeds being developed.

We emphasize that the focus of the discussion in this section is on the process we followed to develop the design seeds and on how consideration of the model levels or elements in the WDA and CTA modeling led to proposals for specific types of design seeds. Also, we limit the discussion to only some aspects of the model analysis. A detailed exposition of the entire model analysis and the design seeds that emerged from mapping SME statements onto the ADS and the Decision Ladder would require more space than the present paper permits.

4.1 Consideration of potential difficulties

Each SME statement referred to a task or some specific observation they found noteworthy about a task. Analysts considered the task or the observation to determine where the most likely human demands and difficulties lay. This was done from a broad consideration of the likely perceptual, cognitive, metacognitive and collaborative work demands operators must deal with. For instance, might a specific task be demanding because of the difficulty for the operator to notice crucial information?; or that there are many things to keep track of?; or that it requires the comparison and transformation of information that varies in terms of its modality (e.g., visually, aurally)?; or, might it simply be that the task is time consuming at a time when the operator is already under time pressure?

The process by which analysts considered potential difficulties associated with SME statements could certainly have been pursued further by following a deliberate line of questioning with the SMEs themselves. However, for a variety of reasons (the internalization of tacit knowledge and skills, insufficient time, etc.), we found it more effective for analysts to make these considerations themselves. Usually, this was inextricably tied to mapping potential operator demands or difficulties along its cognitive dimensions. We treat this next.

4.2 Mapping the cognitive basis of difficulties

A number of themes were readily apparent when identifying computer-based design seeds based on cognitively related difficulties. Although a considerably more extensive list than this was actually developed, we provide some examples in Table 4 above for illustration. The full list was developed from a consideration of the Wickens model of human information processing [9] (see Fig. 3 below). The table above links some element of cognition with the design seed theme that seemed to be predominant, and briefly describes the support hypothesis that can be associated with the theme. As a means to an end, we found that considering SME statements from the perspective of potential cognitive difficulties was successful in quickly generating a potentially rich vein of design proposals in the form of design seed themes. However, to pin down the specifics of design seeds we turned next to the WDA and CTA mapping results.

4.3 Consideration of the WDA modeling

The Abstract Function level of a work domain refers to the underlying laws and principles governing activities in that work domain. The closest element of cognition to the Abstract

Function is novel problem solving; the operator takes what he knows generally about an area and applies it to a new situation without any known and defined processes and procedures. Design seeds for this level in the Abstraction Hierarchy must therefore permit flexible styles of working. Indeed, design seeds at the Abstract Function level must only bound the extent of permissible activity in accordance with the underlying laws and principles, leaving the operator free to act in anyway he wants beyond these laws and principles.

A number of design seeds were identified that allow the operator to work flexibly to solve some new problem. One of the simplest was the provision of a free text entry field that can be associated with a contact and written to a database. This is because it is impossible to anticipate all the information, or the nature of that information, an operator may want to record about a contact. Consequently, the provision of a free text field (in addition to the strictly bounded data fields) in which to write anything presents an underlying principle ("you can record whatever interesting fact about a contact you want") but does not impose a process on to it ("it doesn't matter what that information is"). Many other design seeds were developed that present information in such a way as to reduce the load on the operator's working memory while engaging in novel problem solving. This could be done via specific display entities or via composite display metaphors that provide a general visualization of the conceptual constraints on operator activity.

The Generalized Function level refers to the processes adopted in the work domain. The closest elements of cognition at this level are the mental models, scripts and schemas that feed decision making, situation awareness and other higher-level cognitive functions. A large number of design seeds were identified at this level of abstraction. Many were automated support functions such as the drawing of the most direct navigable route between two points. This supports the simple process of planning a route by proposing a basic route to start with. The operator could then more easily engage in the 'what iffing' that should accompany planning because they can focus on the other considerations rather than the route itself. Operators also consider specific tactics for specific situations. These comparison processes could easily be supported with an unobtrusive support tool that leaves the operator free to generate a more elaborate solution. One example would be a representational aid that links information to enable comparisons of the mission, the constraints and the entities in the work environment.

The last level from our selection discussed here is the Physical Function level of a work domain, which refers to the entities that exist in the work domain (e.g., contacts in local and operational environments) and their capabilities. The closest element of cognition to this level is Situation Awareness (SA) so that by designing to address this level, we are attempting to improve SA. The design seeds identified focus on the visualization and display of each entity in the work environment and its capabilities. For instance, some design seeds refer to monitors for divergences from expected behaviour. Other seeds refer to databases of common, expected or repeated behaviours that can assist the contact identification process. The objective behind the latter seeds is to use knowledge of the contacts' existence, observations of their behaviours, and 'best guesses' of their capabilities to determine who they are and provide some sort of contact recognition support. By doing this job for the operator, the system is freeing up time and effort to be directed toward developing better courses of action and getting inside an opponent's decision-action cycle.

In summary, it was possible to draw parallels between the Abstraction Hierarchy and elements of cognition, and develop specific design seeds at each level of the hierarchy from the mapping of SME statements onto their level of abstraction in the Abstraction Hierarchy. We also attempted this for the Part-Whole Decomposition of the WDA modeling, but we have found that its principal contribution to the development of design seeds has so far been largely indirect. For example, its consideration suggested the necessity to tailor the level of presentation of and access to the information in a seed to the decomposition level at which it is to be used. Information serving higher levels is more likely to present an overview, allowing the operator to drill down into topics of interest. Information serving lower levels is more likely to present the detail initially, permitting the formation of the overview from the detail.

4.4 Consideration of the CTA modeling

The CTA modeling also resulted in a number of design seeds being identified. However, the nature of the analysis meant that it was more difficult to correlate design seeds with specific data-processing activities or states of knowledge in the ladder. To overcome this, we aggregated steps in the Decision Ladder in a similar manner (see Fig. 2 above) to that in which the Wickens model of human information processing [9] (see Fig. 3 below) aggregates information processing. The ladder was split into three stages, corresponding to the stages of perceptual encoding, central processing, and responding. We also added a 'working memory' stage to form a bridge between perceptual encoding and central processing.

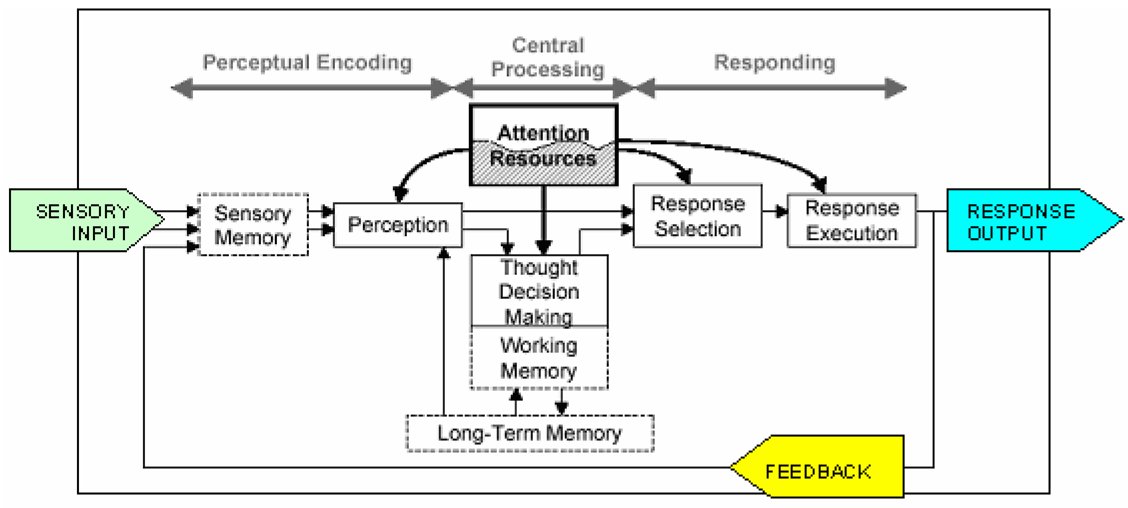

Figure 3. Wickens information processing model (adapted from [9])

When conducting the analysis of the results of mapping SME statements onto the ladder, it became apparent whether the emphasis of the associated operator activity lay at an early, middle or late stage of information processing. Predictably, those statements judged to rest largely at the early stage of information processing related to perceptual encoding resulted in specific design seeds that focus on bringing a stimulus to the operator's attention, or retaining that stimulus in a location for the operator to access and use quickly and easily in decision-making and problem-solving processes. Practically, these design seeds are auditory or visual cues, followed by displaying objects that convey the new information so that the operator remembers that it exists without running the risk of it being forced out of working memory.

The next stage in the mapping described above is ‘working memory’. This stage suggested design seeds in the form of some external representational aid (i.e., in a display) that offloads the burden on the operator of remembering the information. Traditionally, this would be a list or set of discrete display objects. However, this work has suggested composite, synergistic display objects that are a result of data fusion, the consideration of the information being conveyed, the cognitive operation to be performed on that information, and the mental model to be triggered. These features can help overcome working memory limitations and move information processing seamlessly from perceptual encoding, through working memory, to central processing.

We discuss here one more stage, the central processing stage of information processing. This stage encompasses the realization of the current system state, the knowledge of what state the system needs to be in, and the resolution of any ambiguity. In this work environment there can be a great deal of ambiguity. The resolution of this ambiguity and the determination of what the system state should be represent significant challenges to automated systems. The Decision Ladder, in contrast to the Abstraction Hierarchy, provides more detail about the precise aspect that should be addressed by the design seed. For example, in central processing how can the operator determine the system state or resolve ambiguity? What information is required by the operator to arrive at the next state of knowledge? What process is adopted by the operator to arrive at a new state of knowledge?

This latter point is perhaps the most illuminating with respect to identifying design seeds from CTA modeling. This analysis identifies leaps and shunts (‘shortcuts’) in the Decision Ladder. Interestingly, our analysis also identified additional shortcuts that do not conform to the strict definitions of leaps and shunts [3]. Design seeds were identified to accommodate expert operator ‘shortcut’ processes. As a simple example of this in the scenario SMEs developed in the CDM interviews, when tasked with escorting a tanker operators already knew that they were not with the tanker and therefore had to plot a course to the tanker. In turn, this involved assembling a large array of information for consideration. One design seed to address this would be to automatically link mission objectives with ongoing work activities and have the system monitor other systems’ states and invoke the appropriate subroutines or decision support tools.

Many of the design seeds that resulted from analyzing the CTA models focused on the automation of work activities; for instance, automation of route plotting, automation of determining what weapon system to use in response to threats, automation of searching for things that might affect a plan. In comparison to the WDA, the CTA resulted in design seeds that were much more focused on taking the active problem-solving and decision-making role away from the operator. This possibility may not always be the most appropriate use of the analysis, as this may deskill operators and render them less able to conduct novel problem solving. However, by focusing on supporting the operator in achieving the various activities in the Decision Ladder, rather than focusing on actually automating them, Decision Ladders were also found to support a design approach that is complementary to the human operator.

5. **Moving from Design Seeds to Interface Concept**

Traditionally, the identification of design seeds that help jumpstart a design process is an implicit process, subjugated to the development of a support concept. However, by explicitly identifying the ‘small’ kernels (i.e., the seeds) that comprise a support concept, a system developer can consider them individually for the manner in which they complement the overall concept. This eliminates the addition of functionality to a support concept during the design process that can often result in subtly disjointed elements of a supposedly 'integrated' design.

Considering all the design seeds produced in this work has led to the development of a coherent, integrated interface concept. The interface concept represents the manifestation of several design seeds that were identified during the analysis discussed above. Figure 4 illustrates only one component from that interface concept. This specific component was developed to support MTPC work on a HALIFAX Class frigate. Some details on this component have previously appeared in [5]. We provide a summary here.

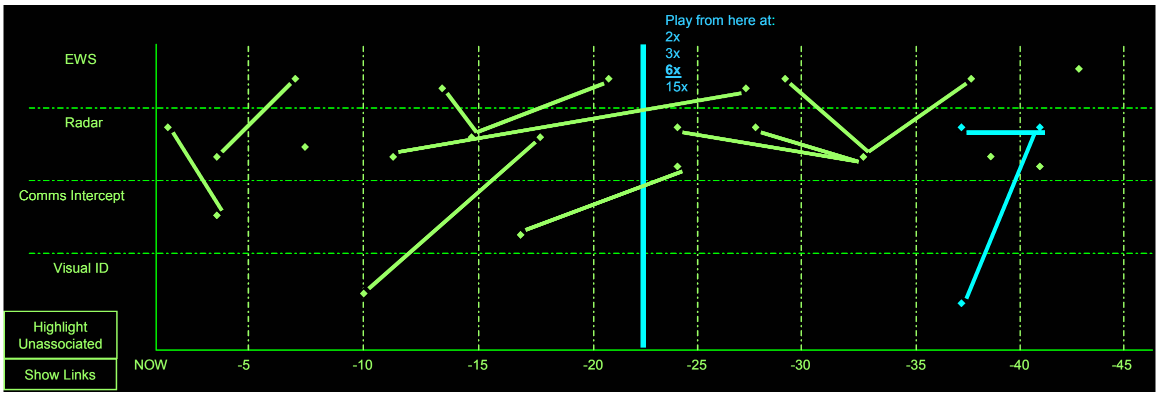

Figure 4. Time-based data display component of interface concept

The time-based data display in Fig. 4 was designed to allow operators to keep track of data (e.g., inputs from the Electronic Warfare Supervisor (EWS), radar, communications intercepts, visual means) across time and spot trends and possible links through the graphical linking (via lines) of related information. Operators can ctrl+click different information 'points' to associate different data in the time-based window, and this will automatically be entered to a database and presented in the target information display (a different display component) when any point associated with that target is selected. Lines can be suppressed through use of a 'Show Links' toggle to permit the user to reduce clutter on their display. Links are also shown on the situation display (another display component). The time of appearance of data (a point on this display) will also be automatically entered into the database. Operators can click and drag out a vertical 'time' cursor from the 'NOW' position to any position along the time axis and replay the appearance of data from any point at various faster than real-time speeds. Replay also replays in the situation display. Clicking on any piece of data (points) in the time-based data display will show links (if links are suppressed), highlight related (target) entry(ies) on the ORBAT window (another display component), and the situation display and will invoke the corresponding information display.

An in-depth exposition of how this display concept and others emerged from the process described in this paper will be covered in future publications. In reality, the process of moving from design seeds to a coherent and integrated support concept can be summarized as an evolutionary 'conversation' between Human Factors specialists, software and hardware engineers, and, crucially, operators. The exact manifestation of a design seed will depend upon many things, such as Human Factors' best practices along a number of dimensions, software and hardware capabilities, operator preferences, and new empirical work focusing on the fit between different aspects of a display. For example, composite display objects in which data is fused will rest on research into the modes of information display required, and the manner in which these requirements can be integrated.

6. Conclusions

The experience of identifying design seeds using the process described in this paper was interesting from a number of perspectives. First, design seeds and a viable, integrated support concept were developed within three weeks of data collection with SMEs. That is to say, the data was collated and structured, Work Domain Analysis and Control Task Analyses were conducted, design seeds were identified and the manner in which they could be put together to create an integrated support concept was considered. These activities were performed by four analysts. This result is in marked contrast to the impression of an onerous process that is often communicated by the CWA literature.

The next point refers to the large number of design seeds developed during this work. In fact, regardless of the 'style' of statement taken from SMEs (i.e., task or observation), it was possible to develop a design seed for every single one. In the development of new systems, this would provide ample inspiration for design teams to create innovative and useful new systems. The ready development of design seeds lends credence to the notion that CWA, and specifically WDA and CTA, are merely means to an end; that the important aspect is the development of useful design outcomes. As such, the reliability and utility of the data and the analysis may in the end be of less importance than what they tell us about design seeds and what we can do with them.

This leads to a final point specifically about design seeds, that their identification should mark a return to data collection. During this work, an 'open-ended' approach to data collection was taken in order that SMEs could define their own problems and resultant design seeds would be based on SMEs' own implicit knowledge of what comprised the difficult elements of their work. However, this means that the data collection sessions necessarily covered a great deal of ground, with limited opportunities to gather all the detail to fully develop all seeds. As a result, the data was 'patchy' at times in terms of a consistent level of detail and uncovering all aspects of an activity. Because of inconsistent data, analysis could also potentially be inconsistent. Design seeds could still be identified though, and many of them can be considered quite insightful. However, in order to fully 'flesh out' a design seed, it is indeed necessary to return to the SMEs and investigate the design seed's area of application in meticulous detail. This was not pursued during this work, but would be a logical next step.

Although the focus of this work has been to develop design seeds of a computer-based nature, the process developed was also found to be worthy of exploration for its potential extension to the development of seeds addressing an even broader set of design considerations, including training and operator organization.

The resource and time constraints inherent in this work have meant that the utility of CWA-based approaches to system development has been stringently tested, and the result for the process we developed and followed based on our exploratory design framework has been positive. This work has also challenged the perspective that is normally adopted in a CWA: CWA was developed primarily with a view to the revolutionary design of a work domain (i.e., not constrained by an existing instantiation of the domain); however this work has applied it to the evolutionary design of an individual's task (i.e. not the whole work domain) in an existing work domain. As far as we know, this may also be the first work to use CDM to do a CWA; the first to use the ADS and Decision Ladders to model SME 'statements'; and the first to use Decision Ladders to model shipboard Operations Room activities. Finally, this work also appears to be the first to convincingly demonstrate a concrete, traceable progression from data, to work analysis and modeling, to the identification of design seeds and support hypotheses, based on a consideration of CWA results and of cognition.

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