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Design and User Evaluation of an Interface Prototype that Adapts to the Operator’s Cognitive Task Load

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Abstract

Earlier research showed the importance and usefulness of the Cognitive Task Load (CTL) model and method in the design and evaluation of new systems in process control. The CTL model describes task load using three variables: time occupied, task set switching and level of information processing. After validation of the model, an interface was developed that supports specifically on those three load factors. To enhance operator support, current research shows the design and evaluation of different levels of automation for this interface. User evaluation shows very positive results on the support system in general and findings are in line with earlier research. However, results show no effects between levels of automation on performance and mental effort. Possible explanations can be found in the experimental and interface design. Modifications to the interface, to achieve higher situational awareness, trust and better results on performance and effort, are discussed. This paper concludes with a short overview how critical areas of effort, performance and CTL can be determined. Together with real time CTL information these areas can be used to adapt support for optimal human machine operation by switching between levels of automation.

1 INTRODUCTION

Designing highly complex interactive human-machine systems in process control has been subject of many studies. Ongoing automation causes a radical change in the position of the operator from monitoring and control to supervision. Grootjen et al. (2006c) defined six main problem areas for naval ships: (1) Increasing complexity; (2) Changing of information type and volume; (3) Increasing system autonomy causing ‘out of the loop’ operator problems; (4) Task integration from different domains; (5) Decreasing personnel and training budgets; (6) Increasing legislative constraints.

Human-centered design methods are often proposed to establish for the human a central and distinct position from other aspects of the system (Stanton and Baber, 2006; Neerincx, 2003). In human-centered design of a new system, different configurations are tested and evaluated. This iterative process stops when the most efficient configuration, which fits on a generic set of constraints, is established and can be implemented. However, a different configuration could be more efficient for a specific situation or subset of constraints, although it would be less efficient generally. Even if we follow a “classical” human-centered design method, the six defined problem areas make it extremely difficult to develop static support concepts that cover all critical situations. Therefore, support systems in dynamic domains should be dynamic as the domain itself. For example Niwa & Hollnagel (2001) use dynamic mapping of alarm support to enhance operator performance in nuclear power plants. Another example is the alarm handling support system of Dutch navy ships, which has different levels of automation (Mulder, 2003).

Recently, a method for the design of user friendly support systems has been developed (Neerincx, 2003; Schneider-Hufschmidt et al., 1993). The method results in an interface concept which is of great value and increases efficiency and effectiveness. This cognitive support was specifically designed to optimize the CTL of the user. Until now, it was evaluated for static function allocation and interface design. Static function allocation refers to the process of distributing tasks and functions at design time, by analyzing both system and operator competences. However, to deal with the mentioned problems, we think the operator needs specifically personalized support which can differ in time (Neerincx et al., 2005). This paper presents several steps in the design (Section 2) and evaluation (Section 3) of such support. Section 4 presents the conclusion and discusses future steps in the design process.

2 DESIGN OF INTERFACE

Oppermann (1994) states that the user interface is the part of a system responsible for getting input from the user and for presenting system output to the user. A system that adapts either of these functions to the user's task or to the characteristics or preferences of the user, is an adaptive interface. This section presents the CTL model and the design of a static and adaptive interface concept naval ship control.

2.1 Model for Cognitive Task Load

Starting point in the design of our adaptive interface is the CTL model of Neerincx (2003). Neerincx developed a CTL model (Figure 1) which distinguishes three load factors that have a substantial effect on task performance and mental effort.

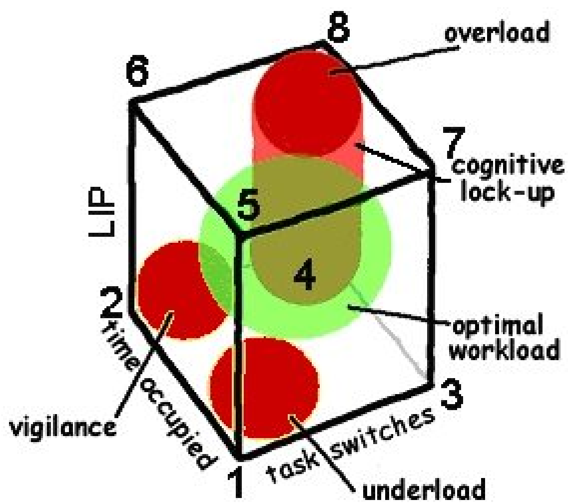

Figure 1. Dimensions of the CTL model (see text for explanation) (Neerincx, 2003).

The first load factor is the classical factor percentage time occupied (%TO). The second load factor is the level of information processing (LIP) (cf. the skill-rule-knowledge framework of Rasmussen (1986). To address the demands of attention shifts, the cognitive load model distinguishes task-set switching (TSS) as a third load factor. Figure 1 presents a 3-dimensional 'load' space in which human activities can be projected with regions indicating the cognitive demands that the activity imposes on the operator. In the middle area, CTL matches the operator's mental capacity. At angular point 8 CTL is high and an overload situation occurs. Angular point 1 represents the area in which CTL is not optimal due to underload. When TO is high, and LIP and TSS are low, vigilance problems can appear (angular point 2) (Grootjen et al., 2006b). When TO and TSS are high, lock-up can appear (Neerincx, 2004).

2.2 Static Interface Concept for Operational Support

After validation of the CTL model, Neerincx & Lindenberg (2000) developed four support functions and an interface that influence CTL specifically on the three load factors. This section will first give a short description of these support functions, together with support instances. An explanation of the interface on communication level will be given using Figure 2.

1. An *information handler* supports on the CTL variable TO by combining and structuring information. Alarms are ordered in categories, the required interface component is presented automatically (process-based) and hyperlinks are used between and within components. When possible, graphical in stead of textual information is shown.

2. A *rule provider* supports on LIP by provision of normative procedures. Context specific procedural information is presented.
3. The *diagnostic guide* supports on LIP and guides the operator in complex diagnostic processes.
4. A *task scheduler* supports on TSS by providing an overall work plan. A clear task overview is given, check marks can be used for process state indication and alarms are prioritized.

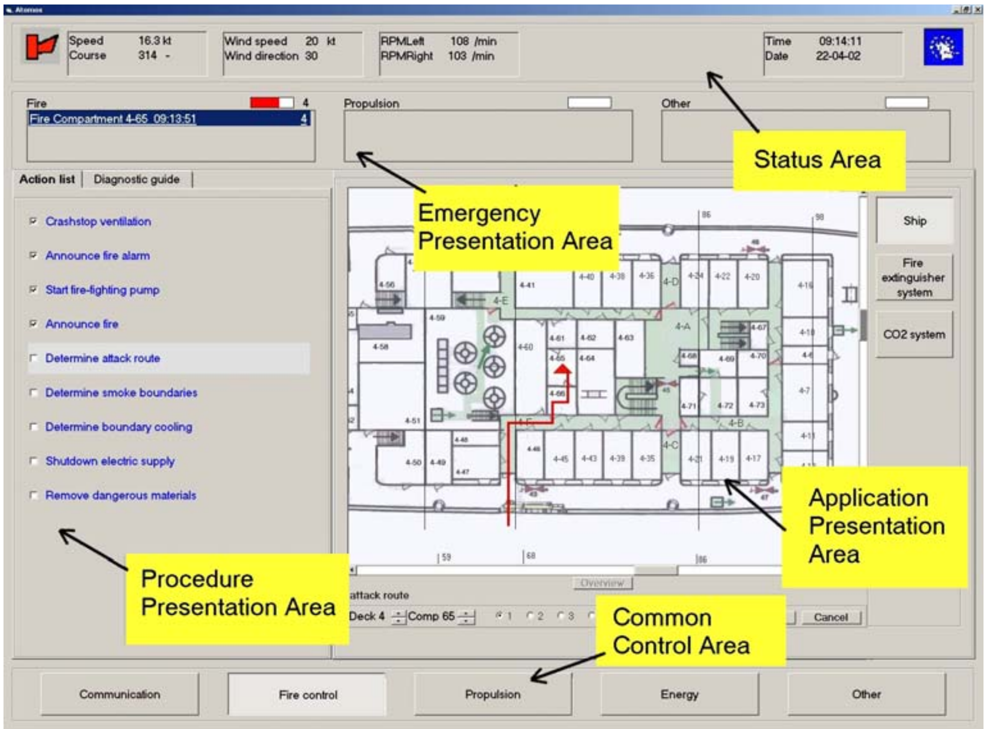

Figure 2. Static interface, designed to influence the variables of the CTL model.

Figure 2 shows an example of the user interface during a fire emergency. On a communication level five different areas can be distinguished:

1. The status area is shown on the top part of the screen. In this area real-time information is presented and an alarm bell is used to indicate the alarm status.
2. The emergency presentation area shows the emergencies with their time of occurrence.
   - The alarms are categorised into groups (Fire, Propulsion and Other).
   - Each emergency is presented as a hyperlink that ‘loads’ the corresponding procedure in the procedure presentation area. Selection of an emergency is indicated by ‘inverted’ video (blue background).
   - Next to each emergency a number is given to indicate the priority of that emergency.
   - Next to the group name a priority indicator (horizontal bar) and a corresponding number are given, showing the highest priority of that group.
3. The procedure presentation area provides web-browsing functionality and consists of two tabs, the ‘action’ and ‘diagnostic’ tab:
   - The action tab presents a list of all actions that must be performed to deal with the selected emergency.
   - Checkmarks can be placed in the appropriate checkboxes to indicate that a specific step in the procedure was completed. The background of the following step in the procedure is highlighted while the background of the other actions is grey (i.e. the first not check-marked step is highlighted).
   - The relevant application for the current (i.e. highlighted) step is activated and presented automatically in the application presentation area.
   - Unlike the action tab, which is always available, the diagnostic tab is not available most of the time (indicated by being dim). It becomes available whenever the system manager discovers one or more hypotheses about the system’s state and relations between alarms (emergencies); the tab presents them to the operator.

- A toggle switch is presented before each hypothesis to indicate whether the hypothesis is true (Y), not true (N) or still open (no button pushed). Each diagnosis of the relations ends with a 'Finished' checkbox.
- After the operator finishes the diagnosis, the system manager will indicate and explain whether the choices are consistent in a dialogue box. When the choices are consistent, the dialogue box proposes changes in the context model that correspond to the hypotheses assessment. The operator can choose whether or not he wants to approve to the changes. When the operator approves, the changes are made and immediately used to dynamically improve the procedures and the operator returns to the 'Action List' tab that contains the improved procedure. When he disapproves, no changes are made and he is also returned to the 'Action' tab. The operator can do the diagnosis again by clicking the relation tab.

4. The application presentation area in the middle of the screen is used to present the active application. The buttons on the right side of the screen are used to switch between sub-applications.
   - Procedure actions concerning a damage control action in the ships plot contain a spatial advice, given by the system manager in the application area. For example for the action 'determine attack route', the correct attack route, following standard procedures for the current situation, is shown by the system manager (the red line in Figure 2).
5. The common control area contains five buttons, which can be used to switch from one application to another.

2.3 Adaptive Interface for Operational Support

Until now the four support concepts were extensively tested with the interface described in Section 2.2 (Grootjen et al., 2002; Neerincx & Lindenberg, 2000; Grootjen et al., 2006a), and with an added task reallocation feature for dynamic workload scheduling (Grootjen et al., 2007). Following the design principles for adaptive interfaces (Neerincx et al., in press), this section presents the first steps in the design of an adaptive interface. In addition to the interface of Figure 2, three levels of automation are implemented (LOA's) (see also Grootjen et al., 2006a):

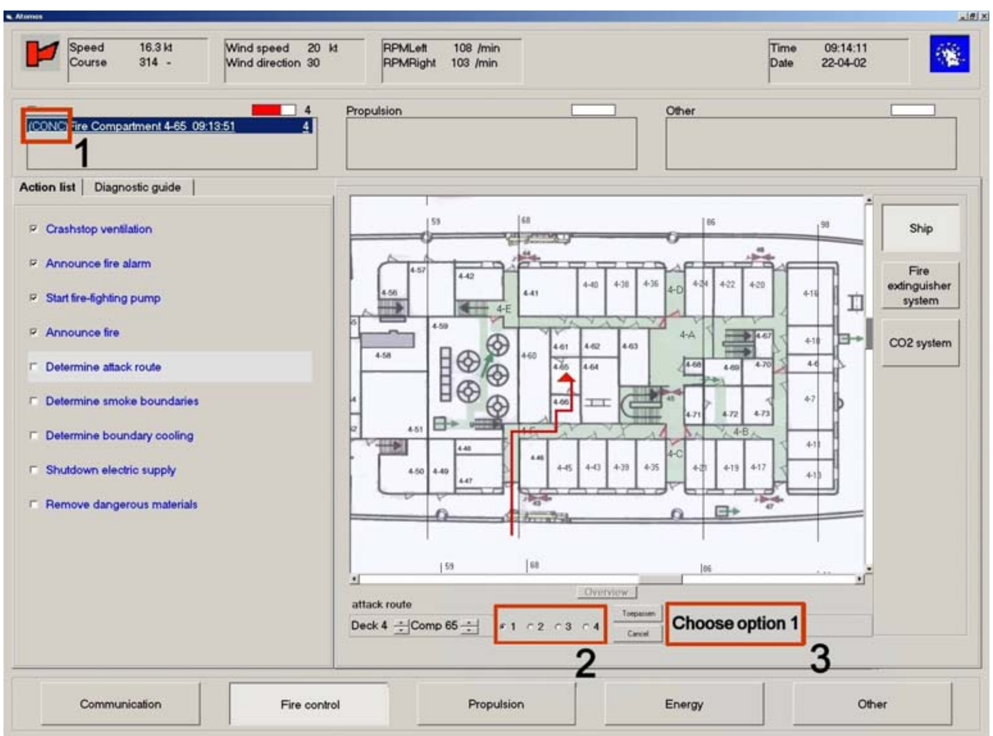

Figure 3. Adaptive Interface in 'concur' mode (1). For each procedure step advice is given in text (3) and show as graphical information by pre-selection (2).

1. Manual. This mode is identical to the interface explained in Figure 2. The operator selects an alarm, a procedure is presented in the procedure presentation area and clicking on a procedure step shows the accompanying information in the application presentation area.
2. Advice. The advice mode is the manual mode with system advices. In the application presentation area advices are given for each step of the procedure (Figure 4). An alarm in advice mode is indicated with the text *(ADV)* in the emergency presentation area (Figure 5).
3. Concur (Figure 3). See advice, and in addition all advices are pre-selected (Figure 3, number 2). This selection results in graphical presentation of the advice in the presentation area. An alarm in concur mode is indicated with the text *(CONC)* in the emergency presentation area (Figure 3, number 1).

Figure 4. Part of the application area in advice mode, advice is given but not shown as graphical information (no selection was made).

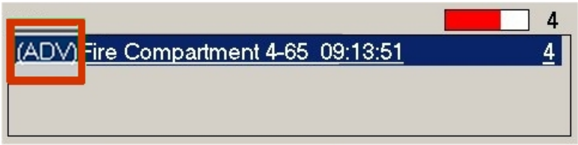

Figure 5. Emergency presentation area showing a fire alarm in 'advice' mode.

3 EVALUATION

3.1 Method

3.1.1 Participants.

For the experiment participants with a maritime background were needed. 34 students of the Royal Netherlands Navy College voluntarily participated, 33 males and 1 female between 20 and 28 years of age (mean= 22.3; SD = 1.7). All participants were 3 to 5 years in service and successfully ended their second year with a practical exam, which guaranteed a certain base level. Three participants with the highest performance scores were rewarded with a bonus. The participants were randomly assigned to a condition. 2 participants were excluded from the results because of a system crash.

3.1.2 Task

The participants' goal was to solve the problems, as good and fast as possible. The scenario was designed following the CTL method of (Neerincx, 2003), and consisted of platform supervision, damage control and navigation related problems. During the first part of the scenario a 'normal' watch on a ship's bridge was simulated. At the end of this part, hostile threats appeared, which resulted in a high task load second part of the scenario. Every participant had to deal with a fire alarm, a low pressure alarm of the fire-fighting system, an alarm concerning the cooling system of the ship, a bilge water alarm, a high temperature diesel engine alarm, a propulsion failure, man overboard alarm and 3 collision warnings. Besides these alarms, they had to plot the ship's position in an electronic sea chart 2 times. How to deal with these alarms was described in a predefined procedure (which is shown in Figure 2, procedure presentation area).

3.1.3 Procedure

Depending on performance, the scenario took about 25 minutes. The total experiment took 2.5 hours. Before starting the scenario an instruction was given (60 minutes) and the participants used the system during a training scenario (20 minutes). Evaluation took 30 minutes. All sessions were recorded using the Observer XT of Noldus (Noldus, 2006).

3.1.4 Design & variables

The experiment has three conditions, with the between subjects factor 'LOA' as independent variable. As described in Section 2.3, the different levels are manual, advice and concur (accordingly 10, 12 and 12 measurements). Participants in all conditions started in the manual mode. After appearance of hostile threats, LOA stayed manual, or changed in advice or concur depending on condition. Only the fire alarm and the propulsion failure alarm changed LOA, the other alarms stayed in manual at all time. The dependent variables were performance (total alarm time, alarm time and number of correct actions), subjective mental effort (Zijlstra, 1993) and 19 questions of an user evaluation questionnaire (5 point scale).

3.2 Results

For performance and effort an ANOVA was used. Data from the questionnaire was analyzed using Mann-Whitney U. We expected to find a higher performance and lower effort score in concur mode compared to advice and manual mode. However, we found no significant results for performance and effort. Results on the 5 point scale questionnaire are presented in Table 1.

Table 1. Results 5 point scale questionnaire (1=not true, 5=true). Significant results ($p<0.05$) are marked.

Question	Mean overall	Mean advice	Mean concur	Sig. Mann-Whitney
1. The advices were difficult to use	1,71	1,50	1,92	0,298
2. The advices were pleasant to use	3,83	4,33	3,33	0,011*
3. The advices were useful	4,04	4,33	3,75	0,038*
4. I get advice with which I don't know what to do	1,21	1,17	1,25	0,623
5. I get advices when I don't want to	1,58	1,50	1,67	0,697
6. I always trust the advice and therefore apply it	2,92	3,50	2,33	0,024*
7. Because of the advices, I'm able to solve problems better	3,96	4,25	3,67	0,241
8. I have more insight in problems because of the advices	2,96	2,75	3,17	0,325
9. Advices disturb my normal way of working	2,50	2,33	2,67	0,350
10. Advices are unnecessary	1,79	1,50	2,08	0,260
11. Applying advices made me forget the selected option	2,58	3,00	2,17	0,219
12. This support system is easy to learn.	4,19			
13. The lay-out of this support system is clear to me	4,00			
14. Sometimes I do not know the next thing to do when I'm solving problems.	1,84			
15. It's clear to me that the wishes of the end user have been taken into account in the design of this system	3,48			
16. This system is getting on my nerves	1,55			
17. The system always does as I expect it	3,58			
18. It's easy to correct mistakes	3,97			
19. I feel I'm in control of the system	3,87			

4 CONCLUSION & DISCUSSION

Ongoing automation in process control emerged a strong need for personalized support which can differ in time. Earlier research (Grootjen et al., 2002; Neerincx & Lindenberg, 2000; Grootjen et al., 2006a; Grootjen et al., 2007) showed the benefits of a user interface which was specifically designed to support on the variables of the CTL model. Obviously, this kind of interface partially prevents CTL problems. Current paper showed the first steps to improve support so CLT problems after system implementation can be prevented. Three levels of automation for adaptive support were defined and evaluated. No results between those levels of automation were found on performance and mental effort. Possible explanations can be found in the experimental design. Compared to the manual condition, too little alarms in the other conditions had a higher LOA. Another explanation can be found in the interface design. Some operators did not detect the advices or only did at the end of the scenario. When they did, they still checked all possible options, which equals the working procedure of the manual condition. As the questionnaire shows (question 6), trust was not optimal. Training and a more clear explanation on how the advices were constructed could provide operator insight and trust. Furthermore, user evaluation shows very positive results on the support system in general (Table 1) and findings are in line with earlier research (Grootjen et al., 2006a).
Based on findings described above, we propose changes to the interface which can be found in Section 4.1. Section 4.2 explains one of these enhancements, the workload feedback display, in greater detail. Finally, linking real time task load, performance and effort to interface adaptations will be discussed in Section 4.3.

4.1 New Adaptive Interface Concept

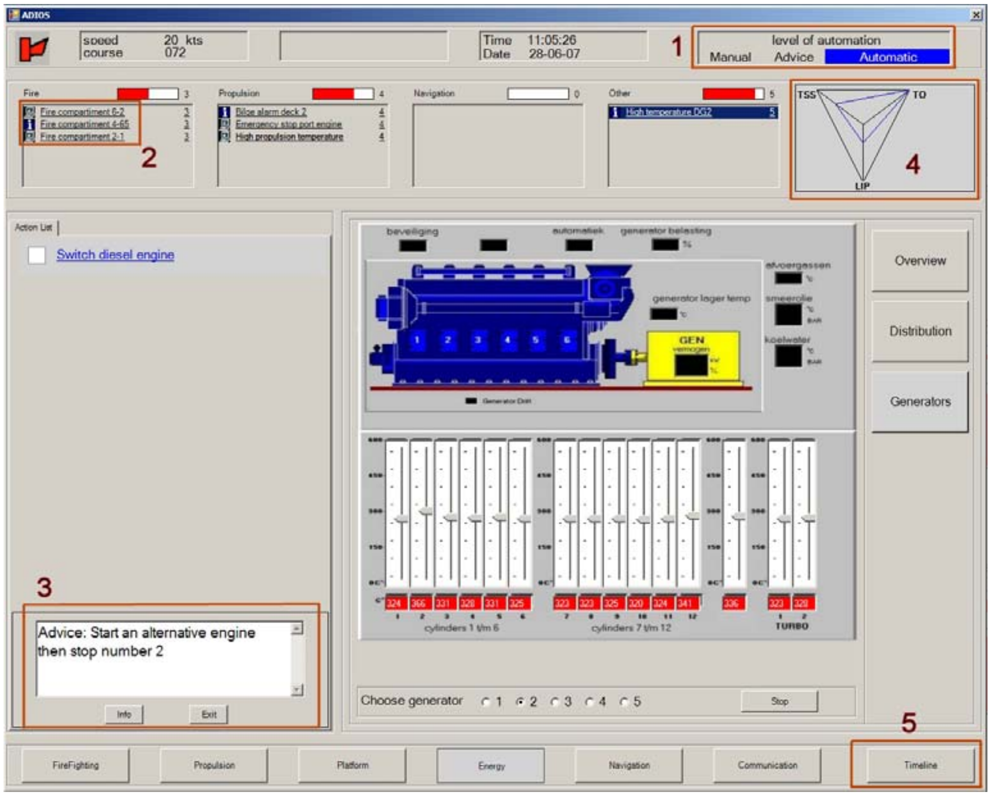

Figure 6. Improved interface: five new features have been added (see text for explanation).

Based on the evaluation of this paper, a new interface was developed shown in Figure 6. Five new features have been added:

1. This area indicates the LOA for the entire system. If possible all active alarms will have this LOA, alarms that do not have an automatic version will be in the highest possible mode.
2. In the emergency presentation area, the LOA for each of the alarms is indicated by an icon:
   Manual Advice Automatic
3. When a selected alarm is in advice mode, the advice is shown below the procedure list.
4. To give the operator more insight why the automation level is changed, a workload feedback display is integrated into the interface. The characteristics of the displayed triangle are explained in Section 4.2.
5. With the button in the lower right corner the operator can open the situational awareness display. See Grootjen et al. (2007) for more information.

4.2 Workload Feedback

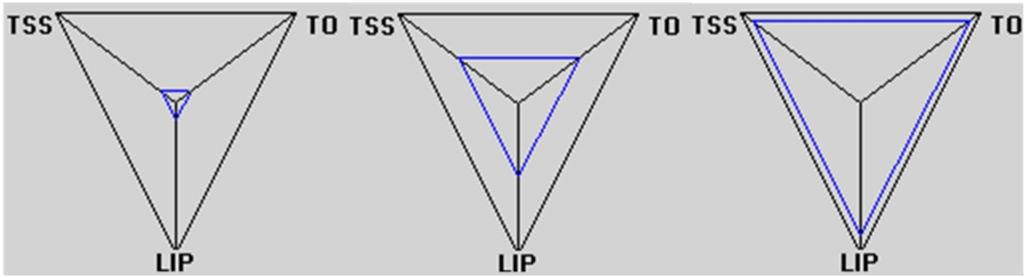

Figure 7. Cognitive task load feedback, the blue lines indicate the operators task load. From left to right: underload, optimal load, overload.

Situational awareness and trust are two major issues concerning usability of adaptive systems. Our next experiment will include a situational awareness display (Grootjen et al., 2007) and will provide CTL feedback (Figure 7). As the LOA is changed based on the CTL of the operator, the CTL feedback can provide insight for the user in this process. However, interpretation of the CTL cube of Figure 1 is not that easy. The operators should be able to know their location in the cube and the accompanying critical areas in the blink of an eye. Therefore a new display has been developed in the form of a triangle, presenting the variables LIP, TSS and TO on the axes (Figure 7). The current values are marked on the axes and connected by blue lines. The advantage of this visualization is the easy recognition of certain shapes of the blue triangle, which can be linked to critical areas like underload, optimal workload and overload. Results on this display will be published at the end of 2007.

4.3 Ship Operator Workload Assessment Tool

The experiment described in this paper did not switch LOA's based on CTL information during task execution. Our goal is to adapt support based on CTL and a large variety of other information. For this purpose, we introduced SOWAT Grootjen et al. (2006c). This tool enabled visualization of an operator's CTL over time and was used to gain insight into CTL variations over the course of an experiment. This first implementation of SOWAT could only process data of a single operator. However, determination of critical areas in CTL space is based on data from multiple operators. Figure 8 shows an extended version of SOWAT which provides this functionality. It shows the results of a critical area calculation for our experiment conducted in April 2007. We processed data of 9 operators (as shown in area 1 of the interface). SOWAT generated 2810 CTL points from this data. The amount of points is determined by the characteristics of the moving CTL time window, which in this case was a window of 60 seconds with 55 seconds overlap (area 2 enables configuration). Once points are generated, they are plotted into cube areas (area 6, 7 and 8). These areas are colored, based on thresholds of subjective effort (area 6), expert performance (area 7) or a combination of the two (area 8). Thresholds can be manipulated using the controls in areas 3, 4 and 5. The cube is presented in 2D by cutting it into four slices, plotted below each other. Each slice represents a TSS value (0, 1, 2 and 3 or higher). Each slice is horizontally divided into five levels of TO and vertically into seven levels of LIP. Black colored areas indicate that there are no data points for this part.

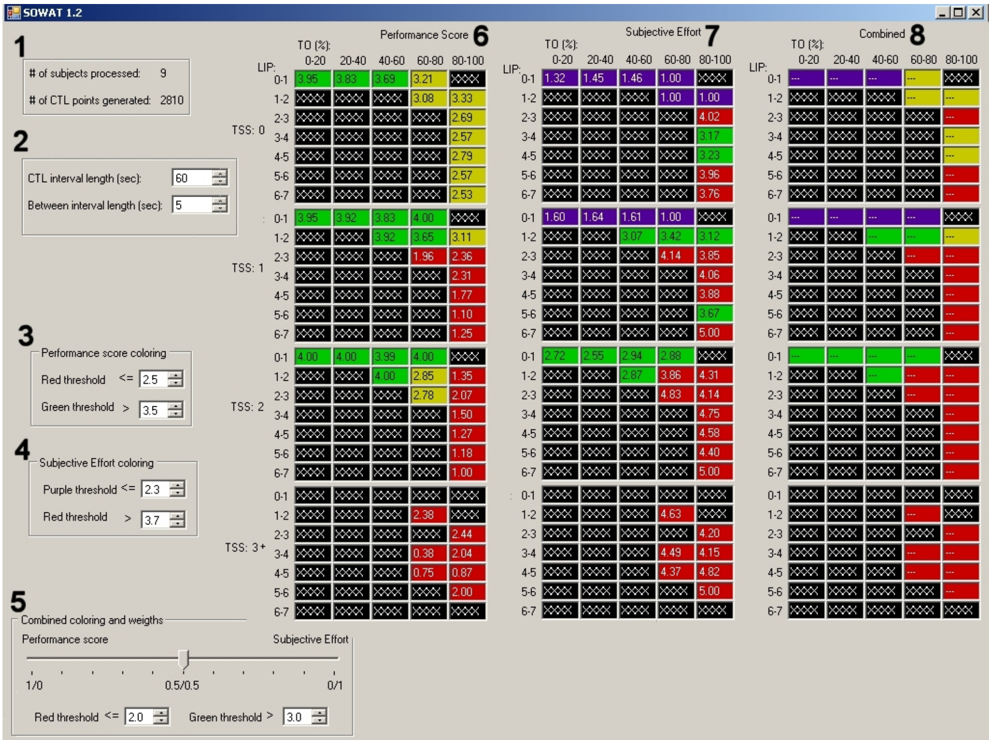

Figure 8. SOWAT interface for CTL cube area analysis.

Once these areas are determined, they are used by the wizard of oz for making decisions about the appropriate automation level for the operator. The wizard interface contains three triangles (Figure 9) in which the critical areas, together with real time CTL information, are shown. Based on the plots and a predetermined set of rules, the wizard makes decisions about the need for changes in LOA. Results will be published at the end of 2007.

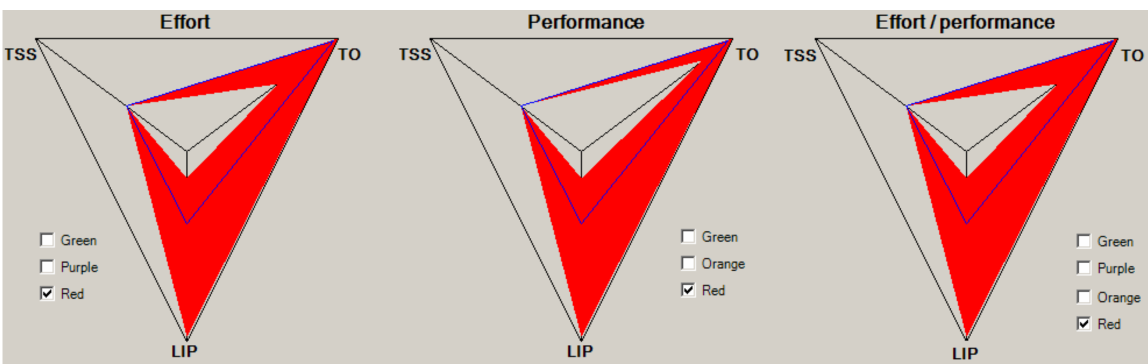

Figure 9. Triangular representations of the CTL cube. The wizard can highlight the different cube areas in the triangles using checkboxes, here the red areas for TSS 1 are shown

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