10th International Command and Control Research and Technology Symposium
The Future of C2

Title: Automated Crew Support in the Command Centre of a Naval Vessel.
Topic: ***Experimentation.***

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AUTOMATED CREW SUPPORT IN THE COMMAND CENTRE OF A NAVAL VESSEL

Abstract

In a decade of an ever-growing information load, rapid developments in information technologies and an increasing pressure to reduce manning, the research institute TNO and the Royal Netherlands Navy are investigating ways to handle these conflicting trends. To this end, a five-year research programme was started in 1999 to explore avenues leading to an increased effectiveness as well as a reduction in manning. The Maritime Command and Control Study was carried out by research scientists of TNO Human Factors and TNO Physics and Electronics Laboratory. The study was organised around several distinct avenues. One of the avenues has been an investigation into a restructured command organisation. A second avenue has been a look at new ways of training and instruction. And a third avenue an investigation into a combination of extensive automation and an improved human interface in order to support the command team with their situational assessment and decision making. The latter investigation has been guided by an analysis of bottlenecks occurring in command and control procedures in current RNLN frigates. Based on this 'hot spot' analysis a number of projects was started with an emphasis on the identified problem areas. The projects were to demonstrate the improvement in the C2 process in terms of decreased workload and reaction times and an increased situational awareness when new concepts of automation and human-machine interfacing were introduced. This paper focuses on these projects.

Introduction

In a decade of an ever-growing information load, rapid developments in information technologies and an increasing pressure to reduce manning, the research institute TNO and the Royal Netherlands Navy are investigating ways to handle these conflicting trends. The development of the command centers of different generations of Dutch warships has been an evolutionary development in the sense that technology-driven modifications and improvements have been grafted on a relatively stable business model. The question is, whether such an incremental development does justice to the possibilities of new technologies and the demands for manning reduction in an ever more complex environment.
To this end, a five-year research programme was started in 1999 to explore alternative avenues leading to an increased effectiveness as well as a reduction in manning. The *Maritime Command and Control Study* was carried out by research scientists of TNO Human Factors and TNO Physics and Electronics Laboratory (now clustered in TNO *Defence, Safety and Security*). In order to get a better grip on the complex matter, the study was divided into three distinct phases: (i) analysis, (ii) partial solutions and (iii) integration.

<u>Analysis</u>
The first phase was an analysis of the bottlenecks occurring in command and control procedures in current RNLN frigates. To that end a matrix was constructed where the C2 processes are plotted against warfare areas and where per combination of C2 process and warfare area it was estimated whether the execution of the C2 process results in a bottleneck due to: (i) (lack of) time to execute the task, (ii) volume (too much information) and/or (iii) complexity (missing or uncertain data or knowledge). To obtain the necessary background data use was made of previous studies and

interviews with RNLN personnel. From this material it became apparent that one of the major bottlenecks occurs while obtaining a good 'situational awareness'. For that reason during the second phase we focussed on solutions to improve the situation assessment process.

Partial Solutions

To further divide and conquer the complexity inherent in the problem statement, in the second phase the projects were organised around three distinct tracks: team organisation, training, and automation and human-machine interfacing. Where applicable, solutions were sought to prevent or reduce the hot spots identified during the first phase.

- *Team organisation*: can command performance and efficiency be increased by changing the team organisation in the command centre, e.g. by reallocation of tasks over resources? This track aimed for new team concepts *making use of existing technology* (and thus made comparisons with the existing CC organization possible).
- *Training*: can command performance be increased by improving the functioning of the human, e.g. by means of better training and instruction?
- *Automation and human-machine interfacing*: can command performance and efficiency be increased through the application of new technology and/or a better, human-oriented interface? This meant an investigation of new ideas of automation and improved human-machine interfacing in order to support the command team with their situational assessment and decision making, without making assumptions about any new team organisation, however. Again, this facilitated a comparison with the existing situation. Here, the focus was on the hot spots identified in the first phase.

Integration

During the final phase a combined command model was worked out, based on the results from the preceding phase. In track 1 the effects of several changes in the team organisation were investigated through work load simulation. In track 3 a concept demonstrator was built and the concepts were evaluated with the assistance of a number of RNLN personnel. In the third phase, the results were combined in a single new team model, with the new simulated team 'using' the new technology (workstation and automation) and again being subjugated to the same scenarios as in the previous phase.

This paper focuses on the project *Automation and human-machine interfacing*.

Automation and Human Interfacing

In order to evaluate some of the proposed automation and support functionality an experimental environment was built in which both aspects could be looked at. The primary aim of the environment was to confront one or more warfare officers with realistic scenarios while offering them an advanced workplace (advanced in terms of men-machine interfacing) and likewise advanced CMS support (automated data fusion functionality). The CMS model is part of a warship simulation (including models of sensors, propulsion and weapons) that resides in a simulation environment together with models of friendly, neutral and hostile ships, aircraft and other platforms. Through a communication layer the CMS is able to interact with multiple operator workstations so that a small command centre can be accommodated.

Automation

The CMS contains level one, two and three data fusion modules that process the incoming sensor data and construct a coherent tactical picture in a separate ‘system space’ that can aid the operators in assessing the situation. This system world view is separate from the standard world view (the ‘recognized maritime picture’ or RMP) that is built and maintained by the operators in ‘user space’. In effect we maintain a double bookkeeping, one for the system, one for the operators.
The advantages of this approach are:

- there is always a clear distinction between the user world view and the system world view;
- system advice is always available (a look into the system world view suffices);
- the system can compare the two world views and thus detect -potentially dangerous- discrepancies.

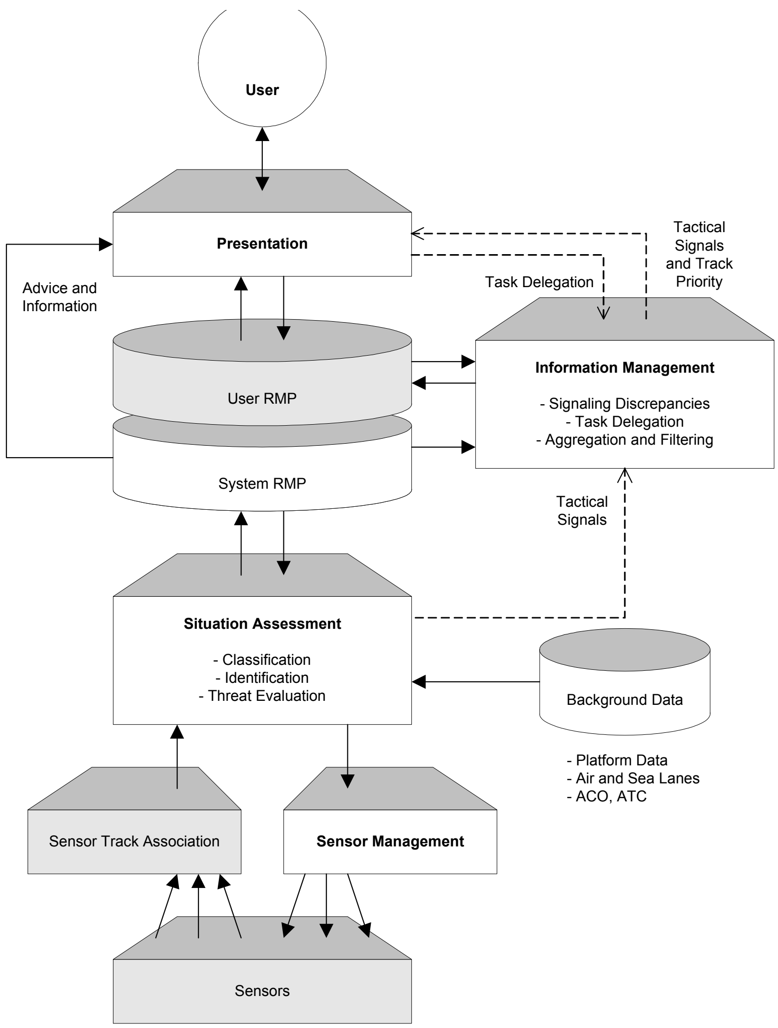

Figure 1. Schematic overview of the architecture of the CMS.

The CMS functionality includes autonomous track association and platform recognition and identification, the results of which can be presented to the crew as advice or copied to the user space. In addition, thanks to the continuous monitoring of all tracks by the CMS, the system can signal the crew if significant changes occur in the state vector of a track.
In all this automated functionality the key phrase is “to keep it simple”. We are under no illusion that it is possible to build a system that can interpret *in a sensible way* every conceivable situation that is thrown at it. It does seem possible, however, to build a system that can assess simple situations and monitor them continuously. In this way the crew is freed from repetitive, monotonous tasks and consequently has more time to concentrate on the difficult and the ‘fuzzy’ situations that are much harder to interpret: air tracks that are outside air lanes, vessels that creep along with the own ship’s movements.

<u>Track fusion</u>
Because a lot of work has already been done on automatic track fusion and it has been shown to be feasible, in this program we have assumed that this task can be executed by the system, so sensor tracks are autonomously fused into system tracks.

<u>Classification</u>
The classification process is also autonomous. It makes use of kinematic data (e.g., height versus speed), classification data from the ESM system and NCTR sensors (multi-function radar in high-resolution mode and IR sensor) and data from other platforms (for example, helicopter and MPA) to infer the platform type. Geometric and temporal data (air lanes, ACO, ATC, formations) are combined with positional data to get a possible classification or at least a ‘characterization’ of the platform. The NCTR classification has been limited to a relatively global discrimination between for instance a ‘large-body, four-engine plane’, a ‘small aircraft’ and a ‘missile’. During the evaluations it soon became evident that even such a generalizing statement can make a significant contribution to the assessment of the tactical situation, especially when it is combined with other observations. A more detailed classification is a much larger technical challenge. The ESM system likewise is limited in its classifying capabilities: we have assumed that the ambiguity of the emitter database will not improve much in the future.

<u>Track Monitoring</u>
Track behaviour is monitored continuously by periodic inspection. This includes things like air lane adherence, but also IFF response. In this way aberrant behaviour (air lane separation, sudden manoeuvring, switching off the IFF transponder) is detected quickly. Each significant change in the state vector of a track is signalled and leads to a re-evaluation of the type and identity of the track and possibly to a changed system identity.

<u>Identification</u>
Identity is assessed by the system using a rule-based system, based on the identity criteria (IDCRITS), e.g.:

if *the track adheres to an air lane and it squawks mode* 3 **or**
if *the track adheres to an air lane and has a large body*
then *the track is neutral*.

A number of implicit assumptions in the identity criteria had to be made explicit. For example, not only the current state vector of a track must be used in the evaluation, but its entire history. Thus the above rules are stated in practice as:

if the track *has always adhered* to an air lane and *has always squawked* mode 3 **or**

if the track *has always adhered* to an air lane and has a large body
then the track is neutral

The use of historic data also necessitates the use of 'trivalent' logic: a criterion is either *true*, *false* or *unknown* to prevent the logical negation of a criterion automatically resulting in the opposite conclusion.

Finally, a distinction was made between 'hard' and 'soft' criteria. The latter are usually the result of ambiguous data or information that can be falsified (like adhering to an air lane or squawking mode 3). Hard rules are always favoured with respect to soft rules. Furthermore the soft criteria generally lead to the temporary identities 'assumed friendly' and 'suspect'. Examples of hard criteria are mode 4 responses and clear, unambiguous classifications.

Tactical Signalling

The system only advises the operators when they explicitly request it with respect to track attributes like classification and identity. It does signal the operators of seemingly important events. Such tactical signals result from a *significant change* in the state vector of a track. Most of the fusion and monitoring processes are able to generate tactical signals, but at first these are redirected to processes at a more abstract level and thus percolate only in a limited manner to the user. New observations, changes in classification, changes in behaviour, etc., are all deferred to the detection of (a change in) *identity* or *threat level*. Thus, changes in the state vector of a track are only signalled to the operators if they result in a change in identity or threat level. As a matter of fact, because we have separate system and user world views, tactical signals are only transferred to the user if the system view increasingly differs from the user world view or additional evidence is found for an existing discrepancy. The existence of separate world views allows the operator to assign a different identity than the one calculated by the system. If identification conflicts occur in this way, the system will silently keep track of these differences. As soon as the system gains access to new information that should lead the operator to re-evaluate the identity assigned by him, the system will warn him.

In this way, a large amount of (implicit) filtering takes place.

Task Delegation

A number of tasks like track association, classification and monitoring are already delegated completely to the system in our demonstrator. We certainly do not propose to let all these tasks be handled completely autonomously, but in this project we have concentrated on the interaction between user and system at the level of identity and threat level.

The identification task can be delegated partly or completely to the system to further lighten the workload of the operator. People, however, will only delegate if they are confident the system can handle the job (the task must be 'easy') and that potential threats do not escape the attention of the crew. Hence, in the case of identification, we are talking about delegating to the system the task of identifying 'relatively easy and safe' tracks. This could be for example the identification of neutral tracks only.

Such a transfer of responsibility can be easily accommodated in the current architecture: in these cases the system is simply allowed *write access* to user space, i.e., the system may copy identities from system space to user space for carefully delineated cases. Task delegation in this case can be pictured as a matrix of system identity versus user identity, where each matrix element either allows or forbids the overwriting of user identity by system identity. In the following table (Figure 2), the system is allowed to assign neutral and friendly identities as long as these do not reflect a large shift in identity (e.g., from suspect to friendly). Other identity assignments remain under user control.

		system identity						
		PENDING	UNKNOWN	FRIENDLY	ASSUMED FRIENDLY	NEUTRAL	SUSPECT	HOSTILE
user identity	PENDING	NA	✓	✓	✓	✓		
	UNKNOWN	NA	NA	✓	✓	✓		
	FRIENDLY	NA		NA				
	ASSUMED FRIENDLY	NA		✓	NA			
	NEUTRAL	NA		✓	✓	NA		
	SUSPECT	NA					NA	?
	HOSTILE	NA						NA

Figure 2. Task delegation matrix for the task of identifying tracks.

Operator Workstation

To further assist the crew, the operator workstation offers a plethora of information in a structured way. The workstation consists of four displays in the form of a flattened "T": a conventional planar tactical display, two displays for situation assessment en decision support to the left and the right and a display presenting the so-called *tactical space* directly in front of the operator. All displays are touch-controlled, eliminating the need for input devices such as keyboard, mouse or roller ball. The operator can set information filters and can change the viewing point of the tactical space.

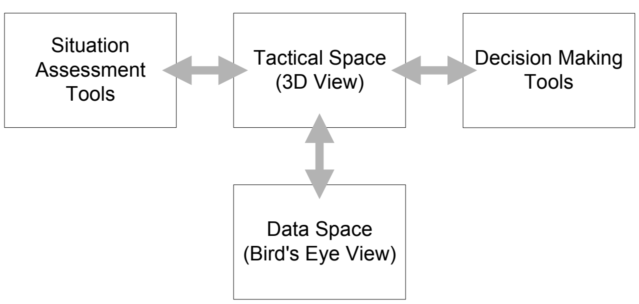

Figure 3. Schematic overview of the operator workstation.

All track information present in the CMS can be displayed, offering the operator insight in the outcome of the data fusion processes of the CMS. The tactical signals from the CMS are translated to visual cues in the displays. Different hypotheses can be assayed using an assortment of support tools. The operator can then adopt the system view with respect to the situation or impose his own interpretation, constructing his own world view in his 'user space'.

The tactical space is an exocentric 3D abstracted presentation of the situation, enabling the operator to view the environment of his ship ‘from the outside’. With the right hardware this presentation is a true stereoscopic projection.
The situation assessment display presents the operator with additional information to assist in the assessment task. Among other things, it presents:

- Track profiles, graphical presentations of parameters like altitude and speed as a function of time to aid in determining the intent of the track.
- Response timeline: a presentation of pre-planned actions in relation to the range at which these actions must be taken. This serves as a memory aid for the operator.
- Identification support based on the built-in identity criteria. For each hypothesized identity the operator can inspect which information supports or contradicts this particular hypothesis and which information that could be helpful is still lacking. In an adjacent box, the user can indicate which identities may be assigned autonomously by the system. In other cases the system gives an advice that may or may not be adopted by the user.

On the right hand display a number of components are present that are specifically aimed at decision support. In our case the one most fully developed was Asset Deployment, an aid to determine the optimal deployment of platform, sensor and weapon systems, more specifically the deployment of Harpoon missiles against hostile surface contacts. Different options are displayed together with the criteria that play a role in the deployment, for instance the possibility of collateral damage versus a missile trajectory that makes it hard to infer the position of the launch platform. The workstation is more extensively described elsewhere (see J.H. van Delft, J.M. Schraagen: *Decision Support Interfaces*, presented at the 2004 IEEE SMC, October 10-13 2004, The Hague, The Netherlands).

Evaluation

The major problem with the evaluation was the fact that there was no possibility of a ‘null measurement’, i.e., no quantitative comparison could be made with the situation in the command centres of current operational RNLN frigates (the Doorman class multi-purpose frigates). Such a comparison would have entailed the double burden of simulation of (a part of) these command centres and the evaluation of a reference group of naval officers. Therefore, the evaluation is a qualitative one, based on the judgement of both the active participants in the scenarios and a number of ‘expert judges’.
In addition to the subjective judgement of the participants, physical and physiological measurements were taken, including registration of head-eye movements and workload, and the scenarios were logged, including machine-generated signals and human-machine interactions.
The participants were RNLN air defence and principal warfare (surface combat) officers that had a mix of experience. The expert judges were officers at the RNLN operational school in Den Helder or with the RNLN naval staff. Their task was to monitor the actions of the warfare officers continuously and to compare their performance with the task execution in the CC of our frigates. To that end, all expert judges had at their disposal a scoring card with an overview of all relevant tactical events in a scenario.
The scenarios were developed in co-operation with officers from the operational school. Two were specifically aimed at air warfare, two specifically at surface warfare and one was a combined AAW/ASuW scenario. Both the AAW and ASuW scenarios were constructed in such a way that the first represented a simpler one in terms of time, volume and complexity (diffuseness, uncertainty) and the other was a more testing one. The combined (AWW) scenario was intended to explore the

boundaries of the human-machine co-operation when one 'warfare officer' was to handle threats in both domains at the same time.

Results

In the period April-June 2003 a number of evaluations with air and surface warfare officers of the RNLN have been successfully completed. In all cases the offered functionality and support were well received. The off-line evaluations indicated that the officers' workload was thought to be reduced and their effectiveness increased. In particular, they were now capable of handling multi-threat scenarios that so far would have necessitated separate AAW and ASuW supervision. Most of the positive reactions were made with respect to the following:

- The autonomous classification and identification, resulting in a fast and consistent picture compilation and a reduction of routine work so that more time remained for overall situational awareness and the inspection of the difficult cases.
- The advice of the system with respect to the identity of a track and the way this was presented.
- The warnings the system gave with respect to changes in the tactical situation, increasing the situational awareness of the crew. More control was perhaps needed to circumvent overload.
- The three dimensional environment of the tactical space was also seen as a way to increase situational awareness. It was not considered a replacement of the classical 2D display, but rather as an addition with its own possibilities, strengths and weaknesses.

<u>Automation</u>

From the logged data some further conclusions may be drawn with respect to the automation.
In the air defence scenarios a large part of the tracks is correctly identified by both the user and the system. Where this is not the case, user and system agree that the tracks should be marked as 'suspect'.
In the surface warfare scenarios a larger part of the tracks remains 'unknown' due to insufficient information. In those cases where user and system do not arrive at the same identity, this is not due to a disagreement with regard to the interpretation of the situation. Both system and user come to the conclusion some tracks are not quite 'kosher' but the user still goes for the other identity ('neutral') and trusts to himself (or the system) to reach the correct identity when more information becomes available.

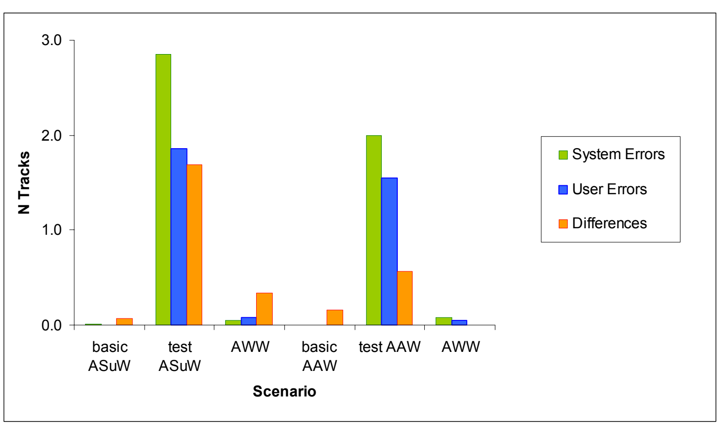

Figure 4 The number of tracks that is incorrectly identified by the system (System Errors) or the user (User Errors) and the number of tracks where system and user disagree (Differences). The total number of tracks was between 35 and 45.

Alerting

Figure 5 below presents on the one hand ‘primary’ or ‘raw’ tactical signals (‘events’) from lower-level processes (e.g., manoeuvre detection) and on the other hand the tactical signals that were actually transferred to the user (‘alerts’). The former may be compared to the small changes in the behaviour of a track that would be of interest to a human operator while deciding on the best identity of that track.

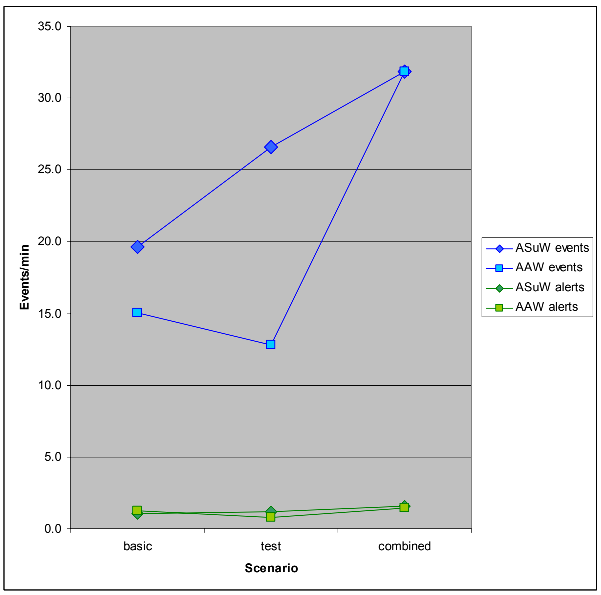

Figure 5 Tactical signals per minute. The upper graphs (blue) are the ‘raw’ tactical signals (events), the lower graphs (green) are the tactical signals used to alert the user (alerts).

From the figure it is clear that the user’s attention is only drawn to a very limited number of events that are deemed important from a tactical point of view, notably because they indicate suspect or hostile behaviour. The increasing number of interesting things (as indicated on the left), as we go from simple to demanding scenarios, is heavily dampened by the automation and the user is only notified of those cases that really merit his attention.
The event graphs clearly show that the AWW scenario has the highest demands with respect to raw data processing. The only surprise was the ‘simple’ AAW scenario that had higher demands than expected by the experts. This did correlate, however, with the physiological load of the users.

Workload

The support of the software and human-machine interface is perhaps best illustrated by a comparison of estimated difficulty of the scenario (Figure 6) and the workload as experienced by the naval officers (Figure 7). For the difficulty of the scenarios the expert judges were asked to assign a score to the scenarios on a scale of 1-10, differentiating between three aspects characterizing a scenario: time, volume and complexity. Because no significant differences were present in these three aspects we have combined them into a single number characterizing the overall ‘difficulty’ of a scenario.

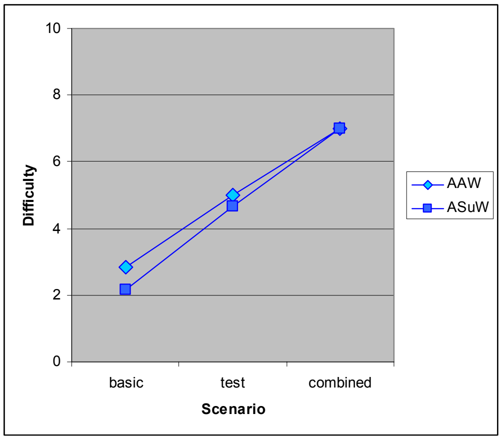

Figure 6. An estimate by the expert judges of the difficulty of the scenarios on a scale of 1-10.

For the subjective workload each of the participants was asked to indicate every one and a half minutes on a scale of 1-5 what their workload was at that moment. The middle of the scale reflects a ‘desired’ load, the ends indicate problematic forms of either ‘underload’ or overload. The results of these measurements indicate that the average workload is at the desired middle of the scale. As in Figure 6, there is a trend toward a heavier workload in a more difficult scenario, but by far less pronounced than the estimated difficulty (or the tactical events) would predict.

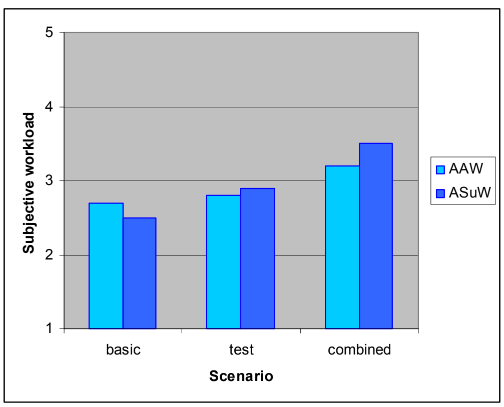

Figure 7. Subjective workload of the active participants on a scale of 1-5.

Conclusions

The concept workstation is a combination of extensive automation and an information presentation and support system. It was evaluated with a number of air and surface warfare officers of the RNLN. All the results indicate that the officers' workload is reduced and their effectiveness has increased. In particular, they are now capable of handling multi-threat scenarios that so far would have necessitated separate AAW and ASuW supervision. The expert judges were of the opinion that the evaluated automation and support concepts give a clear shift of focus when compared to the RNLN multi-purpose frigates. On these frigates situation assessment and the process of picture compilation that serves this assessment still demand significant time and effort. In the new setup more attention could be given to a more global tactical evaluation and decision making.

As a concept demonstrator, not all aspects could be given equal attention, but there are a number of general principles that can be discerned.

- A thorough separation of user and system world view. This always enables the user to look at a relatively 'objective' view of the tactical situation as long as he realises that that view is the result of a limited set of algorithms, rule-based systems or whatever, and thus has a limited value, too. The system world view is a complementary view of the user world view.
- The conclusions of the system in system space and the possible resulting warnings to the user should be based on robust algorithms. In other words, humans should come to the same conclusion when facing the same facts. This should preclude smart systems that can interpret every possible situation (not), but instead promote systems that draw reliable conclusions in limited cases and clearly state "no solution" in other cases. This makes such a system fairly predictable and thus builds trust in the system fairly quickly too.
- In connection to the point above, the exact nature of the algorithmic processing is not very important (for example, we could have employed a Bayesian network for the identification process instead of the rule-based system used), as long as it is clear what information is used and in what way the conclusion is drawn in the system.
- The number of 'signals' to the user can be significantly reduced if these are first handled internally within the system and lifted to a fairly high abstraction level. In our case, we chose identity and threat level, but other attributes are imaginable.
- 'Simple' tasks, finally, can be delegated to the system as long as the user is confident that he will get alerted if one of those seemingly simple cases suddenly starts becoming complex.

Integration in the Overall Programme and Final Conclusions

As indicated before, during the final phase the results from the preceding phase were combined in a single new team model, with the new simulated team 'using' the new technology (advanced workstation and automation) and being subjugated to the same scenarios as in the previous phase. The conclusions from this work can be summarized as follows: for AAW and ASuW tasks it seems possible to realise a significant reduction in the number of people involved (of the command team) by reducing the number of command levels (vertical integration), by integrating the different warfare areas (horizontal integration) and by extensive automation and support of the crew. Both steps lead to a more process-like command configuration in which especially operator tasks are assumed by the system and the remaining personnel operates in a more supervisory capacity. Peaks in the work load can be levelled by making the task allocation and team organization more dynamic.