Assessing Sonar and Target Motion Analysis Stations in a Submarine Control Room Using Cognitive Work Analysis

Daniel Fay[1], Neville A Stanton, Aaron PJ Roberts

[1] Human Factors Engineering, Transportation Research Group, Faculty of Engineering and the Environment, Boldrewood Innovation Campus, University of Southampton, Burgess Road, Southampton, SO16 7QF, United Kingdom

[D.T.Fay, N.Stanton, apr1c13]@soton.ac.uk

Abstract. As part of the Command Team Experimental Test-bed project a submarine control room simulator was constructed. Subject Matter Expert advice was sought throughout to ensure fidelity. However, no dedicated analysis was performed to validate the final result. To resolve this a comparison of Work Domain Analysis outputs was completed to identify levels of fidelity present within the simulator. Outputs were generated from a study at HMS Drakes Talisman, which were compared to previously completed outputs of the simulation facility.

Keywords: Cognitive Work Analysis · Abstraction Hierarchies · Submarine Control Room · Sonar · Target Motion Analysis

1 Introduction

The Command Teamwork Experimental Test-bed (ComTET) project [1, 2] aims to identify and develop new ways of working for submarine command teams. To achieve this a submarine control room simulator was built [2] to conduct statistically high powered experiments exploring design concepts. Subject Matter Expert (SME) input was sought throughout the design, build, and experimentation stages, with SMEs indicating that the simulator was realistic. To formalise this endorsement of fidelity, a comparative examination for select User Interfaces (UIs) (Sonar and Target Motion Analysis (TMA)) using Cognitive Work Analysis (CWA) was performed.

CWA [3, 4] is a framework for modelling complex sociotechnical systems, emphasizing how work should be, as opposed to how it is, conducted [5]. Sociotechnical systems are those formed of technology and actors, human or otherwise. With several trained personnel operating complex technology at any given time, submarine control rooms can be defined as sociotechnical systems. CWA has been successfully used in a variety of domains [6, 7], including submarine control rooms [8, 9]. It has five stages, each for different purposes, although usage is contingent on analysis objectives. For UI analysis Work Domain Analysis (WDA) is typically used [6, 10]. WDA documents objects

within a system, their affordances, and their purposes [4, 11]. This information is represented by an Abstraction Hierarchy (AH), a diagram that splits a system into five horizontal levels of abstraction, ranging from the systems reasons for existing to the constituent physical objects. For each level text boxes (nodes) describe constituent components. Related nodes in adjacent levels are connected by 'Why-What-How' links, which show for any given node, 'what' it is, 'why' it exists, and 'how' it is implemented. With a completed hierarchy it is possible to assess how a system achieves specific goals, or why different aspects exist. This level of detail permits comparison of simulated systems to their real counterparts, with high levels of similarity indicative of fidelity.

Simulator fidelity is defined as the degree to which a simulator can replicate the actual environment [12], citing [13, 14]. It can be split into several types, each pertaining to a different contributing aspect. Of specific interest for ComTET is the replication of task and physical fidelity. Task fidelity is defined as the degree to which task replication exists [12], citing [15-17]. Physical fidelity is defined as the degree to which the physical environment feels like the real environment [12], citing [18]. These were chosen as they directly impact the results of studies performed in ComTET. If future ways of working, both digital and corporal, are to be accurately assessed it is vital that the same tasks are completed using the same physical objects as a real submarine control room.

Previously completed WDAs for ComTETs' Sonar and TMA [1] meant that only their counterparts in Talisman needed creating. Therefore, a study was planned and realised to elicit the required information from SMEs at HMS Drakes Talisman trainer. The compiled WDAs from this study permitted comparison of these stations to derive a measure of fidelity. Nodes on equivalent levels of each AH were compared to understand similarities and differences. This comparison elucidated the degree of convergence present, with high similarities suggesting high fidelity. Similarly, divergence would indicate low fidelity, and a need to improve.

2 Method

2.1.1 Interviews

Interviews were held with five Royal Navy Submariners at HMS Drakes' Talisman trainer over three days. All had served at sea for an average of 856 days (SD = 412.25), and had experience operating Sonar or TMA. Some participants occupied supervisory roles, ensuring holistic analysis. Participation was voluntary.

Participants received drawing equipment (pen, pencil, ruler, rubber, and paper) to utilise freely for communicating concepts. Printed copies of AHs for ComTETs' Sonar and TMA stations were available. TMA functionality in ComTET is a Local Operations Plot (LOP). As the LOP is a component of the Submarine Combat Management System (SMCS) in Talisman, SMCS was compared to CoMTETs TMA. Interviews were recorded using an Olympus WS-831 digital voice recorder, with an additional external microphone. Notes were recorded by interviewers using a notepad and pen.

For the interview, participants were asked to describe their job role, describe their console, and explain its usage. They were encouraged to create supplementary material to aid interviewer understanding and construction of the AH. Each interview was scheduled to last two hours, although this was fluid to allow more time for information elicitation, or less time for duty requirements. The time was provisioned as per Table 1.

Table 1 – Interview Schedule

Activity	**Minutes**	**Description**
Introduction	10	Description research and objectives
Role Scoping	30	Interviewees role defined and scoped
Sketching	30	Sketching of console interface
Means-Ends Analysis	30	Creation of an abstraction hierarchy
Debrief	10	Quick debrief with chance for questions
Slack Time	10	Extra time, for any activity above

Before starting, participants were provided with an information pack containing an information sheet, interview schedule, a demographic questionnaire and a consent form. Upon signing to signify informed consent, and filling out the questionnaire, the interview began. Interviewers introduced themselves to the participants, and the aims of the study were reiterated. Detail about ComTET was provided for context. Interviewer notes were taken throughout to assist with AH construction.

Next, participants were asked to describe their role within the command team, and specify objectives that should be met. For each objective, criteria were elicited that would indicate successful, or otherwise, performance. Participants were allowed to answer freely, although were asked to prefix their objectives with ‘maximise’ or ‘minimise’ to assist with defining clear objectives.

After their job role and objectives had been documented, participants were asked to sketch various interfaces from their console. They were asked to add as much detail as they could remember, however they were not expected to create exact screen replicas. They could use any drawing equipment available. During sketching they were encouraged to speak aloud to match drawings to explanations. The next stage, means-ends analysis, was performed either in parallel or subsequently, depending on participant preference. Participants were asked what functionality each individual aspect of their sketched interfaces, and why it does so. More sketches could be drawn if needed, and these were explored in the same manner. For pivotal processes, participants were asked to write the process down using lined paper whilst explaining each point for clarification.

Once participants had finished explaining how their station looks and works, their attention was drawn to the corresponding ComTET AH diagram. It was explained, but they were not required to absorb all shown information. They were asked to identify any differences between their role and its ComTET equivalent. They were asked to

disregard the bottom two levels, as the interfaces were different hence generating different Physical Objectives and Object-Related Processes nodes. However, if they had feedback it was noted and incorporated.

Finally, the participants were debriefed. The interviews purpose and what had been covered were reiterated. Participants were asked if they had any questions, and then thanked for their time, concluding the interview.

2.1.2 Observations

To ensure holistic coverage of stations and to mitigate unintentional omissions from interviews, a series of observations in the trainer were also conducted. Their purpose was to physically observe each console, and to consolidate experimenter knowledge. Personnel volunteered their free time during simulation runs to either provide a running commentary of interface usage, or to demonstrate their usage, answering questions in situ.

Experimenters used a notepad and pen to capture elicited information. For running commentaries, personnel stood behind working operators during running scenarios and vocalised key points of action. Operators were not interrupted as they were training. This procedure enabled experimenters to place understanding of the system into the context of actual usage. For station demonstrations, an operator would talk through specific procedures of importance, navigate through screens so detail sketches as well as notes could be made, and guide experimenters through practical use of the system. There were no fixed timings, nor topics, for observations. Rather they were held ad hoc in response to training demands on the submariners, personnel availability, and experimenter queries.

3 Comparison of Abstraction Hierarchies

Two AHs for Talisman were created, one each for Sonar and TMA. For each station, the nodes on each level were compared to their ComTET counterpart. The higher three levels will be discussed on an individual node basis, however the bottom two will be discussed in a combined holistic manner. This is due to the number of component nodes, and their close relationship.

3.1 Sonar

Functional Purpose:

The overall goals of operators in both simulators were largely the same, although Talisman operators observed the additional goal of making effective usage of available Sonar arrays. This is due to physical restrictions placed on Talismans simulated arrays, which have an upper limit on how many different bearings may be listened to simultaneously. In ComTET this restriction does not exist, and is therefore is not taken into consideration for the station.

Values & Priority Measures:

There exists significant variability at this level. Only two measures are directly comparable, '*Maximise Contact Detection*' and '*Maximise Signal Clarity*'. The ComTET measure of '*Maximise Known Contact Information*' is split into two for Talisman: '*Maximise Information Passage up the Command Chain*' and '*Maximise Rote Execution of Gun Drills*'. The three remaining ComTET measures, '*Minimise Counter Detection*', '*Maximise Safety of Operations*', and '*Maximise Mission Objective Completeness*', were not included in Talismans measures. This is because senior management take on these roles in Talisman, therefore absolving operators of a need to do so. However, this is not absolute, operators can feed information up the chain of command if they deem it necessary to directly influence meeting these measures. The remaining measures for Talisman all regard the efficacy of operators when using their station and communicating data. There are no direct comparisons for ComTET, however efficacy is implicitly expected. It is hypothesised that the explicit inclusion of these measures for Talisman can be directly attributed to the values of the Royal Navy in being an effective defence organisation.

Purpose-Related Functions:

The general function of Sonar is the Detection, Classification, Localisation, and Tracking (DCLT) of contacts. These are represented in both simulations by '*Detection of Contacts*', '*Classify Contacts*', '*Gain Speed Estimates on Contacts*', and '*Transfer Information About Contacts*'. In ComTET two additional general functions, '*Interpreting/Predicting Contact Actions*', exist. These are undertaken within Talisman, however typically not by Sonar operators, and as such are not included. A General Function specific to Talisman is '*Workflow Construction and Execution*', which relates to measures pertaining to efficiency and accuracy. The emphasis on these measures requires that general functionalities be available to directly support this.

Object-Related Processes / Physical Objects:

There were largely common physical objects and associated affordances for both systems. This is due to the prominence of waterfall displays. Generally, all waterfalls consisted of '*Bearing Tape'*, '*Time Tape*', '*Waterfall Area*', '*Traces*', and '*Contact Markers*'. While the representations of these Physical Objects differed, they are largely comparable. Similarly, their Object-Related Functions are comparable. Aspects outside of the waterfalls exhibited aesthetic variability, but afforded similar, if not the same, functionality for both simulations.

3.2 TMA

Functional Purpose:

Both ComTET and Talisman had the same overall purposes, to '*Generate a Tactical Picture*' and '*Supporting Higher Command Activities*'.

Values & Priority Measures:

Again, there exists significant variability at the measures level, however, comparisons are still present. The combined ComTET measures of '*Maximising Knowledge of Contacts*' and '*Maximise Information Gathered About Contact*' can be equated to Talismans '*Maximise Information Transfer*' and '*Maximise Look Ahead Steps*'. These measures are about collecting as much information as possible for a contact, and ensuring that its future intentions are known. The ComTET measure '*Maximise Solution Integrity*' is present in Talisman as two separate measures, '*Maximise Solution Accuracy*', and '*Maximise Solution Working Time*'. As with Sonar, there were four measures included only in ComTET, as in Talisman they are performed by senior management: '*Maximise Safety of Operations*', '*Minimise Own-Ship Detection*', '*Maximise Mission Objective Completeness*', and '*Minimise Threats from the Enemy*'. Again, Talisman had explicit measures of effectiveness and accuracy. These were '*Maximise Effectiveness*', '*Minimise Errors*', and '*Minimise Communications from the Operations Officer*'.

Purpose-Related Functions:

The general purpose of TMA is generating and maintaining the tactical picture. This is represented by the general functions '*Choose Contact*', '*Create Solution*', '*View Solutions*', '*Assess Solutions*', '*Ensure Solution Accuracy*', '*Refine Solutions*', '*Merge Solutions*', '*Split Solutions*', and '*Remove Solutions*' in both simulations. There were no simulation specific general functions.

Object-Related Processes / Physical Objects:

Base components were found to exist in both simulations, such as '*Contact Markers*', '*Cuts*', and '*Own-ship'*. However, due to the extended capability of Talismans' SMCS, compared to ComTETs' TMA, similarities existed on a more atomic level than Sonar. This means that while Physical Objects represented similar objects, with similar Object-Related Process, how they were arranged lead to highly divergent interfaces. As expected, the closest similarities were observed comparing LOP implementations, with different areas of Talismans interface diverging to greater extents.

4 Discussion

In both simulations Sonar and TMA exist for the same reasons, but their measurements of success are different. It is thought this disparity is a result of their environment. Talisman is a Royal Navy facility, so its measures of success will be derived from the Navy, whereas ComTET is an experimental laboratory and will use an experiment orientated set of measures. The included measures in ComTET are ones that can be measured experimentally, and can be achieved within the projects scope. The equivalence of Functional Purposes, but with differing Value & Priority Measures, indicates that ComTETs stations suggests that they are appropriately included and evaluated in a contextually appropriate manner.

Usage of different interfaces invariably led to different Physical Objects, and subsequently different Object-Related Processes. Consequently, physical fidelity is reduced. However, an essential degree of fidelity is maintained by common interface aspects, such as Sonar waterfalls or TMA cuts. These interface commonalities are mainly core objects required to carry out Sonar and TMA, suggesting that a reduction of physical fidelity can be attributed to non-essential Physical Objects. Thus, while not exhibiting high physical fidelity overall due to different interfaces, a common core for essential components makes a strong case for medium physical fidelity in ComTET.

Congruent Purpose-Related Functions for both interfaces suggest high task fidelity, despite differing interface designs. These differences create different task completion pathways using the available Physical Objects and their affordances, but do not preclude completion of required tasks. While Object-Related Processes could be interpreted as smaller tasks, for example rotating a dial, they are not factored in determining task fidelity. This is because if one submarine used a dial and another used a slider to control a value for completing a task, it would not change the fundamental nature of the task. For the Royal Navy's varied fleet these differences will be inherently present, but submariners are trained to perform tasks irrespective of them. Therefore, disparate Object-Related Functionality does not detract from the high task fidelity exhibited in ComTET as a result of synergistic Purpose-Related Functionalities.

5 Conclusion

In order to ensure experimental validity regarding Sonar and TMA User Interfaces for ComTET a comparison was required with a submarine control room. The comparison control room chosen was Talisman at HMS Drake. Cognitive Work Analysis was chosen to perform the comparison as the method was created for analysing complex sociotechnical systems. Abstraction Hierarchies had already been completed for ComTET, but not for Talisman. Subject Matter Expert input was sought to construct these diagrams for comparison. A study was performed at Talisman with five currently serving submariners over three days. Participants were interviewed and observed to gain a holistic understanding of their stations User Interface. Once all interviews were completed, Abstraction Hierarchies for Sonar and TMA were created.

Comparison of Abstraction Hierarchies for ComTET and Talisman demonstrated that ComTET exhibits a high degree of task fidelity with a medium degree of physical fidelity for Sonar and TMA. This establishes confidence that findings and recommendations from ComTET would be similar to results from using Talisman, whose generalisability to real world applications is well established as a submarine command team training facility. Predicating real world applicability is vital, ensuring a tangible realisation pathway for outputs of the ComTET project.

Acknowledgements

This work was funded by the Defence Science and Technology Laboratory (Dstl) on behalf of the Ministry of Defence (MOD)

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