Examining social, information and task networks in submarine command and control

Neville A. Stanton and Aaron P. J. Roberts

Abstract— **Submarine control room operations have not changed much over the past 50 years, despite introduction of new technologies. This study sought to catalogue current operations as a baseline for comparing new ways of working. Three scenarios were selected to be examined in both high and low demand: returning to periscope depth, dived tracking and inshore operations. The scenarios were run in a submarine simulator with a currently serving submariners from the Royal Navy. The flow of information throughout the submarine command team was examined using Event Analysis for Systemic Teamwork (EAST). EAST models collaborative teamwork via three networks; task, social, and information. Results show that the social interactions, information transition and focus of tasks are different depending on the particular operation being completed and the work demand placed on the command team. There are particular information elements that are fundamental across all scenario types. Task and communication load is not evenly distributed across the team, with potential bottlenecks identified between the Sonar Controller and Operations Officer roles. Implications of the results are discussed alongside recommendations for future research.**

Index Terms—**Submarine, Team Work, Communications, Networks**

I. Submarine Command and Control

Submarines are deployed by many countries in support of numerous duties, from coastal protection and patrol to support scientific research in regions that are difficult to access [1, 2]. Aside from the completion of mission objectives, a key priority of submarines is optimizing the safety of submariners on board and other vessels sharing the ocean [3], although accidents do occasionally occur [4]. Safe submarine operation requires the integration of large volumes of data from numerous instruments and sensors [5, 6]. The ways of working have developed across a century of operations and so reflect a high state of evolution, but that does not mean that they cannot be improved upon [7]. Advanced technologies are routinely implemented retrospectively; often without the sociotechnical performance of such upgrades being formally assessed [8, 9]. The pace of technology advancement can lead to advanced sensor and algorithmic capabilities but the issues of effectively integrating and utilizing such information to improve performance are a problematic [5].

The sensors, instruments and interfaces on a submarine are designed to assist tactical decision-making; however, assessing precisely how each part of the system contributes to supporting this overall aim is a challenge [2, 6, 9]. Such an understanding will facilitate the design of future systems within submarine control rooms. The Commanding Officer (CO) may be the only individual holding a complete tactical picture but even the CO is not explicitly aware of all information processing and transactions between staff in the control room prior to such awareness being attained [5]. Decision making relies upon good teamwork and communication [10]. Such processes can become the limiting factor in determining workload of the team, rather than the work itself [11-13]. The manner in which a team is configured can greatly influence how communication takes place and ultimately how effectively a team can perform [14, 15].

Previous work has provided valuable insight into one of the key operations routinely performed by submarines from a sociotechnical perspective, such as returning to periscope depth from below 60 meters [7, 9]. Nevertheless, the focus of submarine operations has shifted away from deep ocean areas to the completion of operations in coastal littoral zones, with high volumes of contacts and in environment conditions that may reduce sensor capabilities [16]. It is therefore important to examine submarine command team functionality in different conditions of demand (e.g., greater volume of contacts) and whilst completing different operations (e.g., surface operations). Hunter, Hazen, & Randall [17] conducted a well-controlled experiment examining the impact of a novel integrated information display on the war-fighting capabilities of a submarine command team from a sociotechnical perspective. The rigor of such work should be commended, however the generalizability of such work is limited due to only one scenario type being used and the focus of the work being relatively narrow. The purpose of the research contained within the current paper is to compare different scenarios of operations with a currently operational command team to better understand the nature of their work.

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II. METHOD

A. Participants

A team of 9 currently operational submariners from the British Royal Navy were recruited. Due to security issues and recommendations from the Ministry of Defence Research Ethics Committee (MoDREC), the demographic information presented is limited. All participants were male with an age range of 25 – 46 and met all requirements to be operational submariners. The cohort was selected to be representative of the command structure, comprising: 1 x Commander, 1 x Lieutenant Commander, 2 x Chief Petty Officers, 1 x Petty Officer, 2 x Leading Rating and 2 x Able Rating. The roles they fulfilled, as described in table 1, were: Sonar Operator (SOP), Target Motion Analysis (TMA), a Sonar Controller (SOC), Operations Officer (OPSO), Periscope (PERI), Ship Control station (SHC) and Officer of the Watch (OOW). All participants had completed sea deployments. The study protocol received ethical approval from the University of Southampton Research Ethics Committee (Protocol No: 10099) and MoDREC (Protocol No: 551/MODREC/14).

TABLE 1. Overview of roles and main duties

Role	Overview of main duties
OOW	Responsible for directing submarine activity, interpreting the tactical picture to manoeuvres the submarine effectively to best complete mission objectives whilst simultaneously maximizing submarine safety and covertness.
OPSO	Co-ordinate the generation of a tactical picture based upon OOWs requests. Direct and quality check the work of the TMA.s and Facilitates the flow of information from the sound room (via SOC), to the relevant TMA operator. Pass visual information (via PERI) to the TMAs to generate contact solutions.
SOC	Co-ordinate activity in the sound room and responsible for the integration of all sonar data from multiple arrays. Direct and quality check the work of the SOPs. Facilitate the flow of relevant information from the sound room (via OPSO) to the picture room.
SOP	The SOPs are required to sweep the sonar arrays (visually and aurally) to detect potential contacts, seek permission (from SOC) to designate contacts and perform analysis of acoustic data to classify (via narrowband) and generate speed estimates (via DEMON) of contacts. Typically each SOP will operate a different sonar array.
TMA	Generate contact solutions (predict behavior of contacts) by analyzing patterns of acoustic or visual bearing cuts
PERI	Operating periscope and gathering visual information regarding surrounding contacts and any other intelligence (e.g. buildings)
SHC	The SHC responds directly to orders from OOW and must be aware of submarine safety and covertness. Enacting and overseeing changes to own submarine parameters (e.g. course and depth)

B. The Submarine Control Room Simulator

A submarine control room simulator was built based upon a currently operational Royal Navy (RN) submarine. Roberts et al. [8] provide a full description of the building process and the simulator capabilities. In brief, the simulator is comprised of 9 workstations each with two stacked monitors (one touch screen), a keyboard, an input device (mouse) and a communications headset (see figure 1). The workstations run Dangerous Waters (DW) software, a naval submarine simulation developed by Sonalysts Combat Simulations. The software features many networked controllable units from on board a submarine, allowing the completion of submariner command team tasks to fulfill mission objectives.

The positions comprised two Sonar Operator stations (SOP), two Target Motion Analysis stations (TMA), a Sonar Controller station (SOC), an Operations Officer station (OPSO), a Periscope station (PERI), a Ship Control station (SHC) and an Officer of the Watch station (OOW). The submarine simulator has the capacity to record all communications (verbal and non-verbal) that occur between operators with a collection of 10 web-cameras, 2 high-resolution video cameras, 2 ambient microphones and the installation of recording software to capture any transmissions over the five channel communication network.

Figure 1. The ComTET submarine control room simulator showing sound room (left) and control room (right).

An unclassified set of scenarios (see table 1) capturing the widest range of operations submarines routinely complete were selected by Subject Matter Experts (SMEs) and programed in DW. Each scenario lasted approximately 45 minutes, for security purposes only surface vessels were included in the scenarios (merchant vessels, fishing vessels, leisure craft and friendly naval vessels). In all scenarios the behavior of the 'contact' vessels were pre-determined.

TABLE 2. Scenario descriptions

Name	Demand	Contacts	Description
Return to Periscope Depth (RTPD)	Low	4 Fishing	RTPD from deep to send intelligence home, large temporal window of opportunity. All contacts held must be ranged to find optimum course for RTPD.
	High	9 Fishing 3 Catamaran 1 Biological	RTPD as quickly as possible due to severe submarine damage. Attempt to range all contacts to find optimum RTPD course.
Inshore Operation (INSO)	Low	3 Merchant 1 Yacht 1 Freighter	Safely navigate vessel inshore to gather intelligence on land based target. Scenario complete once close enough inshore to adequately photograph building.
	High	2 Merchant 1 Powerboat 5 Fishing	Identify and track 'suspect' contact inshore to gather intelligence on activity and building operating from.
Dive Tracking (DT)	Low	3 Fishing 1 Sailboat 1 Nimitz	Starting at PD, locate and track priority contact (Nimitz warship) in nearby waters, scenario complete when all contacts held have been ranged and priority is tracked.
	High	7 Fishing 2 Merchant 1 Nimitz	Locate and track priority contact (Nimitz warship) in nearby waters, after near Collison forces emergency go deep procedure.

C. Design

This was a single case study design. The independent variables were scenario type (RTPD, INSO and DT) and scenario demand. The dependent variables included all communications that took place between operators within the command team and tasks completed.

D. Procedure

Informed consent was attained from participants whilst a simulator induction was completed. Participants were assigned station roles based upon their operational role within the RN and provided with one hour familiarization training at their workstation. Participants were then told that the first scenario would begin – all recording devices were started and a verbal time stamp was read aloud for synchronization purposes (capturing team transactions and communications directly has many benefits over retrospective methods [18]). Each scenario began with an OOW briefing outlining the mission objectives (see table 1). The OOW led the direction of the scenario tactically, as would occur operationally. When the command team had completed the mission objective the end of the scenario was called, after a short break for refreshments and debrief regarding the previous scenario participants were asked to sit back at their workstation and the second scenario would begin. Each scenario lasted for approximately 45 minutes. This process was repeated until all six scenarios had been completed. Participants were then provided with a full debrief and thanked for participating.

E. Analysis of Data

The analysis used a new shortened form of Event Analysis for Systemic Teamwork (EAST: [19]). This has been used to model submarine command team performance previously [16] (Stanton, 2014). Since its conception, the framework has been applied in many domains such as emergency services [20], aviation [21] and notably naval warfare [7, 9, 16, 22]. EAST models complex collaborative systems through a network approach. The networks are based on transcriptions of all of the communications in the sound and control rooms, for each of the six scenarios. Specifically, three networks are considered: task, social, and information. These three networks are developed directly from the raw data of video and verbal recordings. Social networks analyse the communications taking place between the ‘agents’ working in the team. Task networks describe the relationships between tasks, their sequence and interdependences. Finally, information networks describe the information that the different ‘agents’ use and communicate during task performance. These networks were modelled using AGNA software (version 2.1.1 – a software program for computing the Social Network metrics). The networks were then presented to the SMEs for verification. They confirmed that the networks were indeed valid descriptions of their work.

A number of metrics were derived from AGNA allowing a quantitative assessment of the networks to accompany the descriptive models. Firstly, the global network metrics were calculated as defined in table 3.

TABLE 3. Global network metrics

Metric	Definition
Nodes	Number of entities in a network (people, information or tasks for the purposes of this paper)
Edges	Number of pairs of connected entities
Density	Number of relations observed represented as a fraction of the total relations possible
Cohesion	Number of reciprocal connections in the network divided by the maximum number of possible connections
Diameter	Number of hops required to get across the network

Secondly, the individual nodes in the network were examined, as defined in table 4.

TABLE 4. Nodal network metrics

Metric	Definition
Emission	Number of links emanating from node in the network
Reception	Number of links emanating going to each node in the network
Sociometric	Number of emissions and receptions relative to the number of nodes in the network
Centrality	The sum of all distances in the network divided by the sum of all distances to and from the node
Farness	Sum of each node to all nodes in the network by the shortest path
Betweeness	Number of times a node lies on the shortest path between other nodes

III. RESULTS

A. Social Network Analysis

The six social networks are presented in figure 2a-f with the results of the analysis in tables 5–8. All highlighted metrics in the tables and nodes in networks are discussed in the text.

A1. Global social network metrics

The global network metrics reveal the two densest networks to be the RTPD and INSO high demand scenarios (see table 5). The high demand scenarios required greater input from all members of the command team as there are more contacts to process and the potential for the safety of the submarine to be compromised is greater.

Table 5. Global social network metrics

Scenario	**RTPD**		**INSO**		**DT**	
Demand	Low	High	Low	High	Low	High
Nodes	9	9	9	9	9	9
Edges	33	39	24	37	31	31
Density	0.46	**0.49**	0.33	**0.51**	0.47	0.43
Cohesion	0.34	0.33	0.31	0.39	0.31	0.36
Diameter	3	2	3	3	3	3
Interactions	514	704	1062	944	870	1278

The DT scenario bucks the trend in the sense that the low demand network is denser than the high demand network (see table 5), however the cohesion is also much lower in the low demand network. It is likely that such a difference is based upon the tactic used to complete the low demand DT scenario. The OOW could dive when the contact had been spotted visually. It is also possible for the OOW to remain at periscope depth during DT and periodically raise periscope in a ‘duck and run’ fashion. A comparison between figures 2e and 2f shows that the links from PERI to OOW and OPSO in the low demand condition are more than double of those in in the high demand condition (figure 2f). This suggests a more concerted use of the periscope in the low demand condition.

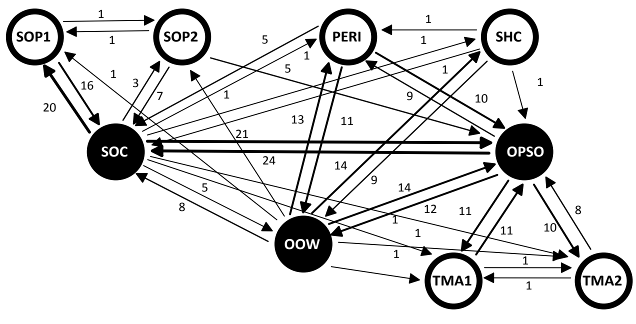

Figure 2a. Social network (RTPD low demand)

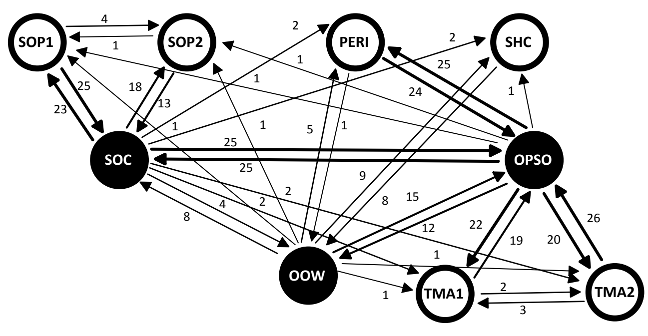

Figure 2b. (RTPD high demand)

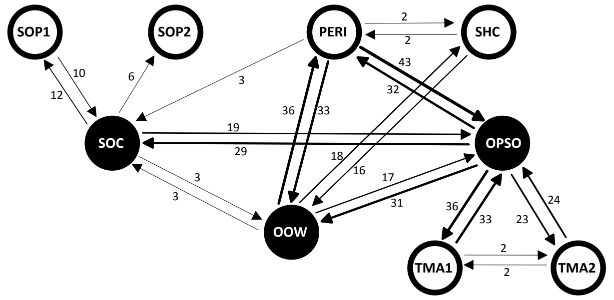

Figure 2c. Social network (INSO low demand)

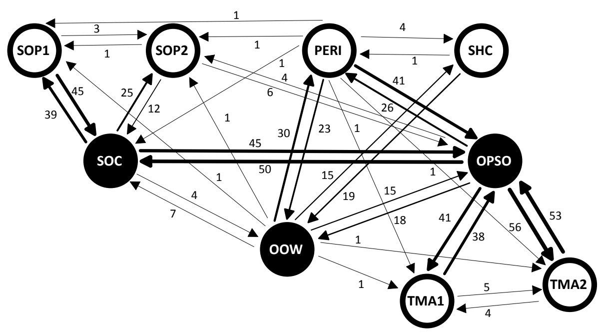

Figure 2d. Social network (INSO high demand)

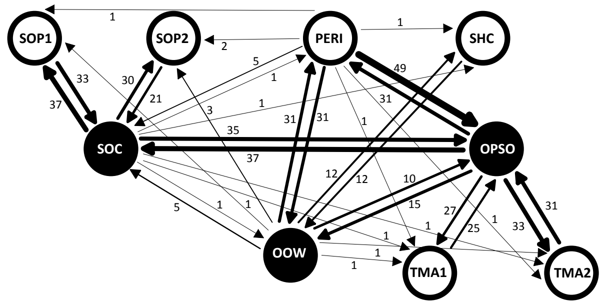

Figure 2e (DT low demand)

A2. Nodal social network metrics

In all scenarios the connection between OPSO and SOC is always particularly strong (see figure 2a-f). The sociometric status of both these operators also tends to be high (see tables 7 – 9). The communications passed between OPSO and SOC are important, as it is this connection that links the sound room and the picture room, without this communication it is impossible to build a tactical picture using sonar data. The SOPS do not routinely communicate with anyone outside of the sound room, it is for this reason that the sociometric status and betweeness of the SOPS is relatively low in all scenarios and their respective farness values are relatively low (see tables 6-8). The impact the SOPS have on the network also varies depending on scenario type, the total emissions and receptions are at their lowest very low during the INSO low demand condition and consistently higher in the DT and RTPD scenarios (see tables 6-8).

The TMA operators have similar values to the SOPS for emissions, receptions, sociometric status, centrality, closeness and farness (see tables 6-8). Everything generated in the picture room by the TMA operators is only communicated to OPSO and it is OPSO who decides how this information might best be used by the OOW and potentially SOC. Similarly, to how the SOPS only communicate with SOC the TMA operators only communicate with OPSO. However, generally speaking, the sociometric status and centrality of the TMA operators is greater than that of the SOPS across all scenarios but particularly during the INSO scenarios (see table 7). The reason behind this may be due to the fact that the TMA operators are required to generate solutions concerning the behaviors of vessels using information from a variety of sources (i.e. visual as well as sonar).

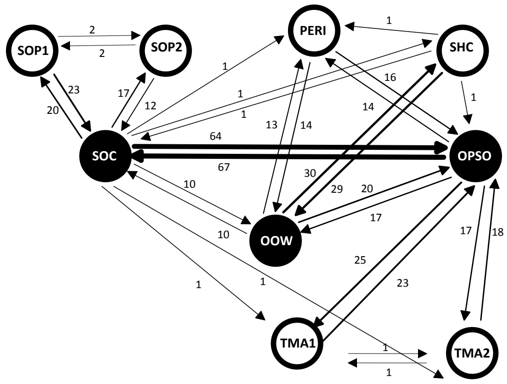

Figure 2f. Social network (DT high demand)

A3. Effect of demand

In both the DT and RTPD high and low demand scenarios SOC had the highest centrality value of all the operators, however for the INSO the centrality value of SOC was lower than OOW, OPSO and PERI (see tables 6 and 8). This is a good example of how scenario type can change the impact each operator has on a network. During the RTPD and DT scenarios sonar information is critical to team performance, SOC is responsible for making this information available to relevant operators, routinely via communications with OPSO and/or OOW.

The operator that consistently has the highest emissions, receptions, sociometric status, and centrality is OPSO. During the INSO high and low demand conditions OPSO has nearly double the sociometric status of the next highest operator and almost triple the amount of emissions and receptions (see table 7). A key reason for this is that OPSO is responsible for guiding the generation of the tactical picture and is integral to providing relevant information to the OOW. A primary responsibility of OPSO is to integrate information from different sources in order to build the tactical picture. For example, the OPSO switches the primary communication link from SOC (auditory information from sonar) to PERI (visual information from periscope) as the situation demands. The number of communications between OOW and OPSO remains consistently high across all scenarios as no tactical decisions can be made without such communications taking place.

The sociometric status of the OOW remains consistently high across all scenarios but is typically below SOC (except during INSO high demand), OPSO and is at similar level to PERI during the INSO scenarios (see table 7). A reason for this is likely to be that the OOW is responsible for making all tactical decisions (e.g. maneuvering own submarine and RTPD).

However, the OOW does not necessarily want to be pre-occupied with every precise detail of how the picture is being built. Rather the OOW wants to be provided with a high level over view of the tactical picture, with more specific detail regarding parts of the picture that demand more attention tactically (e.g. priority contacts). An example of this is that the centrality of the OOW is frequently the highest and the farness and eccentricity of the OOW is typically the lowest. This is due to the fact that the OOW will speak to anyone in the command team that he believes can provide the most up to date information required to build the tactical picture.

TABLE 6. Nodal social network metrics RTPD

	Emission		Reception		Sociometric		Centrality		Farness		Betweeness	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
OOW	53	41	37	25	**11.25**	**8.25**	5.85	5.45	8	8	8.33	10
OPSO	66	107	70	109	**17**	**27**	5.85	5.74	11	8	17.33	15
SOC	53	78	61	71	**14.25**	**18.63**	**6.5**	**5.45**	8	8	19.33	12
SOP1	16	29	21	26	**4.63**	**6.88**	3.77	4.19	**15**	**14**	**0**	**0**
SOP2	12	14	4	24	2	4.75	3.9	4.19	**14**	**14**	**0**	**0**
TMA1	11	21	13	28	3	6.13	3.77	4.19	18	14	0	0
TMA2	8	29	12	25	2.5	6.75	3.77	4.19	18	14	0	0
PERI	26	25	24	32	6.25	7.13	4.68	4.03	13	14	0	0
SHC	12	8	15	12	3.38	2.5	4.18	3.89	12	15	0	0

TABLE 7. Nodal social network metrics INSO

	Emission		Reception		Sociometric		Centrality		Farness		Betweeness	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
OOW	64	73	59	70	**15.38**	**17.88**	5.8	5.04	8	12	10	4
OPSO	146	140	150	142	**37**	**35.25**	5.27	5.76	11	11	14	17.5
SOC	108	115	101	113	**26.13**	**28.5**	6.11	6.37	8	8	17	27.5
SOP1	**33**	**25**	**39**	**22**	**9**	**5.88**	3.87	3.9	**15**	**14**	**0**	**0**
SOP2	**21**	**14**	**35**	**19**	**7**	**4.13**	3.87	3.9	**15**	**14**	**0**	**0**
TMA1	25	24	30	27	6.9	6.38	3.87	4.03	18	17	0	0
TMA2	31	19	36	19	8.4	4.75	3.87	4.03	18	17	0	0
PERI	91	30	67	29	19.75	7.38	5.52	4.32	8	16	3	0
SHC	12	32	14	31	3.25	7.88	3.86	4.32	15	12	0	0

TABLE 8. Nodal social network metrics DT

	Emission		Reception		Sociometric		Centrality		Farness		Betweeness	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
OOW	74	71	83	64	**19.62**	**16.88**	5.36	5.8	12	8	7.5	10.42
OPSO	151	195	136	198	**35.88**	**49.13**	5.9	5.8	11	10	23	19.67
SOC	40	113	45	115	**10.65**	**28.5**	**5.36**	**5.04**	12	12	19	6.08
SOP1	10	48	12	42	**2.75**	**11.25**	3.37	3.63	**19**	**18**	**0**	**0**
SOP2	0	19	6	34	**0.75**	**6.63**	6.56	4.64	**0**	**14**	**0**	**2.25**
TMA1	35	43	38	47	9.13	11.25	3.81	4	17	16	0	0
TMA2	26	57	25	63	6.34	15	3.81	4	17	16	0	0
PERI	81	73	70	57	18.88	16.25	4.92	5.27	12	8	4.5	5.58
SHC	18	20	20	19	4.75	4.88	3.58	3.63	18	14	0	0

B. Information Network analysis

An example of an information network is presented in figure 3 with the results of the analysis in tables 9-12. The content of the information networks is different depending on scenario type and demand, however, there are prominent consistencies running through all of the networks. This suggests there is fundamental information that is critical to submarine command team performance regardless of scenario type and/or the load placed on the command team.

Table 9. Global information network metrics

Scenario	RTPD		INSO		DT	
Demand	Low	High	Low	High	Low	High
Nodes	40	**45**	39	**46**	46	**57**
Edges	340	502	418	518	644	920
Density	0.41	0.57	0.87	0.97	0.95	0.68
Cohesion	0.21	0.25	0.28	0.25	0.31	0.28
Diameter	5	4	4	4	3	3
Interactions	666	1196	1700	2812	2060	2080

B1. Global information network metrics

When examining the overall networks (see table 9) it can be observed that the scenarios with the highest number of nodes are the high demand scenarios. This might be expected as there were more contacts in the high demand conditions therefore more information was required to create a tactical picture and operate safely. The greater number of edges in the high demand scenarios validate this (see table 9), as the information being passed is connected to a larger number of different information elements. This indicates that the generation of the tactical picture is more complex and requires a greater connectivity between information to facilitate understanding. Examination of the nodes within the networks at the individual level reveals a great deal about the (in)consistencies between scenarios (see tables 10-12 and figure 3).

The clearest observation is that certain information elements are consistently passed during all scenarios. Bearing, course, contact, speed and/or knots are present in the top 10 information transmissions during all scenarios. The accurate generation of a tactical picture requires the OOW to be aware of the bearing, course and speed of all contacts – it is from this information that TMA solutions can be generated (including estimates of range) – allowing the submarine to operate safely. The sociometric status and centrality of these information elements are always amongst the highest of all information nodes (see tables 10-12), emphasising that these information elements are the most critical to the command team, regardless of the operation

	Emission		Reception		Sociometric		Centrality		Farness		Betweeness	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Yards	88	152	88	152	4.63	6.76	20.92	25.38	60	81	44.81	12.12
Bearing	**124**	**195**	**124**	**195**	**6.52**	**8.67**	22.41	32.63	56	63	29.11	228.23
Knots	**124**	**179**	**124**	**179**	**6.52**	**7.96**	25.61	29.37	49	70	104.79	135.53
Ship	69	-	69	-	3.63	-	18.73	-	67	-	1.30	-
Vessel	32	-	32	-	1.68	-	19.31	-	65	-	23.68	-
Visual	67	50	67	50	3.53	2.22	19.92	28.55	63	72	10.33	72.01
Speed	**104**	**147**	**104**	**147**	**5.47**	**6.53**	21.64	26.70	58	77	76.18	18.31
Solution	83	164	83	164	4.37	7.29	22.81	28.56	55	72	96.11	82.39
Course	66	148	66	148	3.47	6.58	24.13	26.36	52	78	246.15	13.89
Contact	**93**	**99**	**93**	**99**	**4.89**	**4.4**	26.70	34.85	47	59	183.01	352.32
Sonar	-	118	-	118	-	5.24	-	30.68	-	67	-	174.23
Range	-	154	-	154	-	6.84	-	26.70	-	77	-	18.90

being completed. Furthermore, 'Contact' consistently has the highest betweeness value of all information nodes across all scenarios. This reveals that the knowledge of surrounding contacts is the most important information element for the command team and that knowledge of the 'contact' is fundamental in driving the passage of all other information.

B2. Nodal information network metrics

Information inconsistencies based upon scenario type are observable. The information 'Nimitz' is observable in the DT scenarios (see table 12) but not in the INSO or RTPD scenarios. The Nimitz is the vessel that the command team was instructed to dive track in a covert manner during the DT high and low demand scenarios. Therefore, knowledge of the behavior of this vessel was critical for the command team to complete the primary mission objective. The betweeness value for 'Nimitz' is high further validating that this piece of information is central to the integration of all other information types. In the INSO scenarios the node 'Visual' is included in the top 10 information nodes in both demand conditions (see table 11).

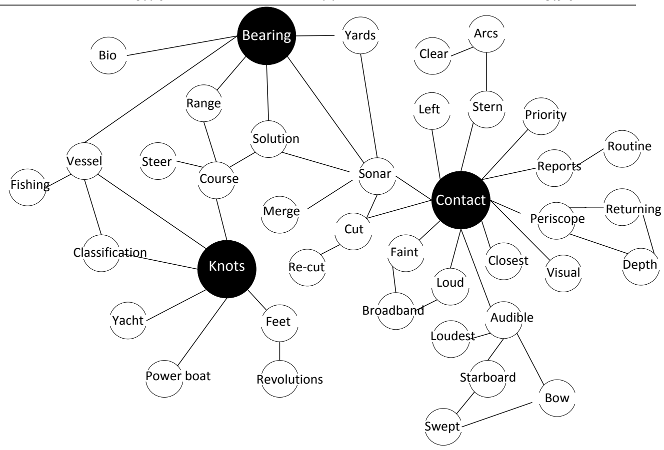

Figure 3 Information network (RTPD high demand)

Table 10 Nodal information network metrics RTPD
Table 11 Nodal information network metrics INSO
Table 12 Nodal information network metrics DT

This emphasizes the fact that during the INSO scenarios periscope is routinely raised periodically to check that the submarine is safe. However, the submarine cannot travel above a particular speed with the periscope raised, so to make headway inshore it is impossible to constantly keep the periscope up. In this sense the contribution of sonar data and visual (periscope) information is equal across the scenario, with both contributing to the knowledge of contact

	Emission		Reception		Sociometric		Centrality		Farness		Betweeness	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Knots	**51**	**68**	**51**	**68**	**2.62**	**3.09**	28.14	26.03	57	71	334.06	120.25
Bearing	**50**	**86**	**50**	**86**	**2.56**	**3.90**	25.87	29.81	62	62	159.29	247.67
Contact	**48**	**127**	**48**	**127**	**2.46**	**5.78**	29.70	34.22	54	54	543.61	386.57
Course	27	61	27	61	1.38	2.77	25.06	26.4	64	70	65.95	66.29
Vessel	35	-	35	-	1.79	-	23.94	-	67	-	59.40	-
Audible	25	-	25	-	1.28	-	21.67	-	74	-	8.70	-
Trawl	25	-	25	-	1.28	-	21.67	-	74	-	8.70	-
Speed	25	-	25	-	1.28	-	21.38	-	75	-	46.32	-
Faint	25	-	25	-	1.28	-	21.68	-	74	-	8.70	-
Holds	22	-	22	-	1.13	-	21.10	-	76	-	0.0	-
Sonar	-	64	-	64	-	2.90	-	30.8	-	60	-	257.80
Depth	-	32	-	32	-	1.45	-	24	-	77	-	22.54
Cut	-	34	-	34	-	1.54	-	24.31	-	76	-	27.09
Range	-	56	-	56	-	2.54	-	25.66	-	72	-	33.83
Yards	-	40	-	40	-	1.81	-	23.39	-	79	-	5.82
Solution	-	30	-	30	-	1.36	-	23.1	-	80	-	3.12

	Emission		Reception		Sociometric		Centrality		Farness		Betweeness	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Contact	**116**	**160**	**116**	**160**	**5.16**	**5.71**	31.79	41.78	58	67	235.70	449.43
Range	99	78	99	78	4.4	2.79	25.97	30.76	71	87	10.29	53.61
Knots	**133**	**129**	**133**	**129**	**5.91**	**4.60**	25.97	37.32	71	75	64.50	353.72
Periscope	82	79	82	79	3.64	2.82	29.30	34.13	63	82	200.38	94.96
Nimitz	**110**	**99**	**110**	**99**	**4.89**	**3.54**	29.74	33.72	62	83	117.09	164.81
Speed	**111**	**104**	**111**	**104**	**4.93**	**3.71**	25.97	33.72	71	83	30.99	92.61
Bearing	**109**	**117**	**109**	**117**	**4.84**	**4.17**	29.26	33.32	63	84	52.14	138.54
Yards	103	-	103	-	4.58	-	26.34	-	70	-	28.56	-
Look	85	-	85	-	3.78	-	27.52	-	67	-	116.48	-
Vessel	82	-	82	-	3.64	-	28.37	-	65	-	42.69	-
Sonar	-	127	-	127	-	4.53	-	36.35	-	77	-	203.10
Depth	-	73	-	73	-	2.61	-	33.32	-	84	-	47.07
Ship	-	74	-	74	-	2.64	-	30.76	-	91	-	74.70

parameters (i.e. speed, course, range and bearing). This is exemplified in figure 3 and tables 10-12, where the node 'Contact' is central to the network with the different visual and sonar information groupings branching off from this, contributing to providing an understanding of the parameters of different contacts.

B3. Effect of task demand

The differences between high and low demand are most prominently displayed during the RTPD scenario (see table 10 and figure 3). In the RTPD scenarios, only 4 information nodes are consistent between the high and low demand scenarios, although 'Knots', 'Bearing, 'Contact' and 'Course' had the highest sociometric status, centrality and betweeness values across both scenarios (see table 10).

In the low demand scenario, the information provides more detail concerning the contact in terms of how 'Audible' the contact is and whether it is 'Faint' or has any 'Trawl'. This type of information provides the operators with a more descriptive tactical picture, such as how loud the contact is. In the high demand scenario, the emphasis is on more general parameters that make up the basics of building a tactical picture such as 'Solution', 'Cut', 'Range' and 'Depth' (see table 10).

	Emission	Reception	Sociometric	Centrality	Farness	Betweeness
OOW brief	1	4	0.19	11.18	159	40.00
Detect contacts sonar	**3**	**2**	**0.19**	12.59	134	69.23
Close sonar contact	**3**	**2**	**0.19**	14.04	120	73.71
Designate sonar contact	**2**	**2**	**0.15**	11.35	153	77.00
Classify Sonar Contacts	**3**	**1**	**0.15**	11.72	137	41.04
Speed estimates	1	3	0.15	11.07	157	3.50
Sonar Courses	1	1	0.08	10.29	154	0.50
Sonar merges	2	2	0.15	12.24	124	68.35
Check cuts	2	1	0.12	11.35	143	33.96
Build Sonar Picture	4	1	0.19	12.96	104	36.45
Generate Solutions	1	3	0.15	12.66	133	63.65
Steer safe course	2	2	0.15	13.04	126	49.00
Refine solutions	3	3	0.23	14.14	109	121.0
Clear Stern arcs	**2**	**3**	**0.19**	13.52	125	**174.5**
Final Reports	3	1	0.15	14.23	108	**174.0**
Silent Routines	1	1	0.08	22.13	38	75.00
Normal Routines	1	1	0.08	22.13	38	75.00
RTPD	1	2	0.12	20.67	28	153.0
Raise Periscope	**2**	**2**	**0.15**	18.11	19	158.0
1st Sweep	1	1	0.08	16.85	6	54.00
Detect Close Visual	1	1	0.08	14.61	3	34.00
First Reports	1	1	0.08	12.74	1	12.00
ESM check	1	1	0.08	15.01	26	69.00
Confirm safe	2	1	0.12	13.78	21	56.00
Raise WT mast	1	1	0.08	13.61	1	12.00
Lower Periscope	1	1	0.08	12.17	24	9.00
Complete mission	0	2	0.08	11.59	0	0.00

TABLE 14. Nodal task network metrics RTPD

The reason for this may be that during the low demand scenarios the operators only have to deal with four 'Contacts' which supports the investigation of such contacts at a highly detailed level. A final observation that is apparent when examining the information networks is that some of the fundamental information elements (e.g. 'Speed', 'Course' and 'Knots') are related not only to the parameters of the 'Contacts' but also to own submarine (see figure 3).

Some information elements are more critical during high demand conditions than low demand conditions within the same scenario type. For example, in the DT scenarios the 'Sonar' node is only present in the top 10 nodes during the high demand scenario (see table 12). Moreover, the betweeness value of sonar is extremely high indicating this type of information is a fundamental information broker in the network. This may be due to the fact that once the priority 'Nimitz' 'Contact' had been identified in the high demand condition (see table 12), the command team dived and relied upon 'Sonar' data much more than during the low demand DT scenario where 'Periscope' would be raised to 'Look' for vessels at particular points to validate the current tactical picture. It is for this reason that the node 'Look' is only present during the low demand DT condition, when periscope was raised more frequently as a tactical picture checker. This is further validated by how high the betweeness value of 'Periscope' is during the DT low demand scenario (see table 12), particularly when compared to the betweeness value of 'Periscope' during the DT high scenario. The periscope was used in a much more procedural manner during the DT scenarios and a more conceptual/exploratory fashion during the INSO scenarios when there is a greater reliance on 'Visual' information (see table 12).

C. Task Networks

An example of a task network is presented in figures 4a-c with the results of the analysis in tables 13 – 15.

C1. Global task network metrics

TABLE 13. Global task network metrics

Scenario	RTPD	INSO	DT
Nodes	27	32	33
Edges	46	54	58
Density	0.06	0.05	0.05
Cohesion	0.01	0.01	0
Diameter	12	12	11
Interactions	92	108	116

There is little to separate the task networks in terms of the global metrics, apart from there are slightly more task nodes (and subsequently edges and interactions) in the INSO and DT scenarios compared to RTPD (as shown in table 13). Density is marginally higher in RTPD compared to INSO and DT.

Something clearly observable from the task networks is the high degree of similarity between scenarios in terms of the tasks completed and the manner in which the tasks are clustered. The primary difference between the task networks relates to the sequencing of the tasks and the manner in which the clusters of tasks interact with each other. The tasks completed during the DT and INSO scenarios are similar, both scenarios begin at periscope depth and involve raising the periscope and Electronic Support Measures (ESM) mast. Initially the focus of the task is based upon using periscope to sweep 360^{o} around the submarine to build a visual tactical picture. This is achieved by detecting all contacts, sending bearing cuts to the picture room, classifying the contact and gaining as much information as possible (i.e. classification, range and course) concerning the contact. The sociometric status of the raising periscope task is higher for the INSO scenario than the DT scenario, this is due to the fact that when the submarine is at periscope depth and navigating inshore the periscope is highly important for ensuring the safety of the submarine.

	Emission		Reception		Sociometric		Centrality		Betweeness	
	INSO	DT	INSO	DT	INSO	DT	INSO	DT	INSO	DT
OOW brief	3	1	0	0	0.10	0.03	31.34	14.74	0.00	0.00
Raise Periscope	**2**	**2**	**5**	**2**	**0.23**	**0.13**	17.63	14.31	318.60	127.00
1st Sweep	1	1	1	1	0.06	0.06	16.59	14.67	125.60	58.29
Detect Close Visual	3	3	1	1	0.13	0.13	16.52	16.03	124.60	75.29
First Reports	1	2	2	2	0.10	0.13	13.84	16.57	110.80	61.04
2nd Sweep	3	1	3	2	0.19	0.09	15.34	14.67	206.20	119.20
Build Inshore Picture	1	-	2	-	0.10	-	22.64	-	11.43	-
Designate Visual	2	3	1	1	0.10	0.13	12.69	16.03	81.60	136.20
ESM check	1	1	1	1	0.06	0.06	16.59	14.67	164.00	71.71
Submarine safe	3	3	1	1	0.13	0.13	16.52	16.03	163.00	88.71
Raise WT mast	1	1	1	1	0.06	0.06	13.43	12.75	50.40	26.16
Lower Periscope	2	3	2	4	0.13	0.22	14.38	18.56	67.40	226.30
Surface	0	0	1	1	0.03	0.03	23.51	39.11	0.00	0.00
Classify visual contacts	1	2	1	1	0.06	0.09	11.42	14.17	34.17	25.00
Range/Course of visual	1	1	1	1	0.06	0.06	11.39	12.53	33.17	20.00
Visually Identify Priority	-	1	-	3	-	0.13	-	14.52	-	97.50
Build visual picture	4	3	2	1	0.19	0.13	14.79	13.52	121.17	37.00
Visual Solutions	2	-	0	-	0.06	-	24.28	-	0.00	-
Dive	1	1	2	1	0.10	0.06	14.27	27.41	53.50	0.00
Detect contacts sonar	**2**	**3**	**3**	**5**	**0.16**	**0.25**	18.71	23.65	223.30	247.80
Close sonar contact	**2**	**1**	**1**	**1**	**0.10**	**0.06**	17.63	18.80	45.50	0.00
Designate sonar contact	**2**	**2**	**2**	**2**	**0.13**	**0.13**	14.27	20.65	160.80	155.21
Classify Sonar Contacts	**2**	**3**	**1**	**1**	**0.10**	**0.13**	13.19	16.20	87.70	33.00
Speed estimates	**1**	**1**	**1**	**1**	**0.06**	**0.06**	12.02	13.77	0.00	0.00
Identify sonar merges	1	1	2	3	0.10	0.13	13.14	17.36	85.70	50.59
Priority Contact sonar	-	1	-	2	-	0.09	-	18.22	-	35.59
Check cuts received	2	3	2	2	0.13	0.16	14.21	18.68	90.53	153.91
Build Sonar Picture	2	3	1	2	0.10	0.16	13.10	17.78	84.70	81.18
Generate Solutions	1	2	2	3	0.10	0.16	13.94	18.45	49.03	59.82
Merge visual and sonar	1	2	2	2	0.10	0.13	14.21	16.20	75.03	40.00
Confirm tactical picture	3	2	5	3	0.26	0.16	18.61	18.10	301.57	40.50
Navigate/Steer vessel	0	2	3	4	0.10	0.19	32.45	17.25	0.00	100.50
Confirm Holding Priority	-	2	-	1	-	0.09	-	15.52	-	54.50
Refine solutions	1	0	2	1	0.10	0.03	22.78	19.42	7.50	0.00
Complete Mission	2	1	0	1	0.06	0.06	27.78	12.98	0.00	4.00

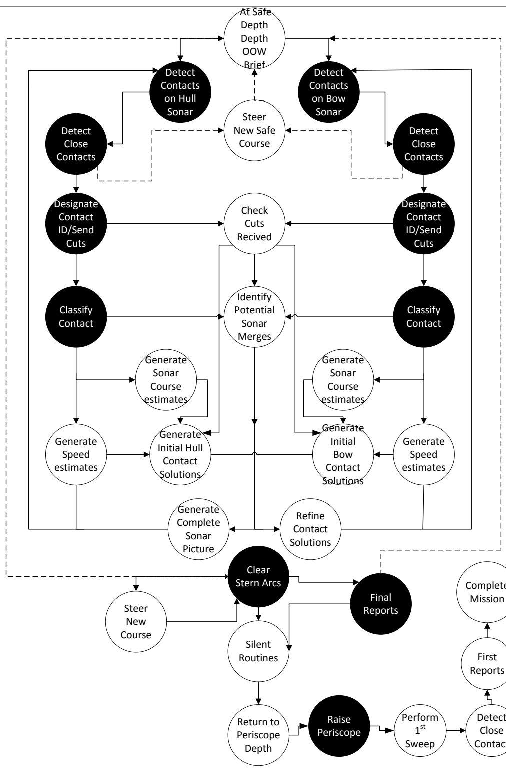

Figure 4a. Task network (RTPD)

The dotted lines indicate tasks that the command team did not undertake (but SME feedback recommended inclusion). When the periscope is raised the ESM masts may be used to detect any electromagnetic transmissions. The tasks that relate to the initial raising of periscope are also observable in the latter stages of the RTPD scenarios, once at periscope depth a visual search is crucial to confirm safety and complete mission objectives. In the DT and INSO scenarios the tasks relating to the raising of periscope are almost identical, except for two notable exceptions. In the INSO the periscope is used to build a visual picture and to facilitate navigation of the submarine inshore. During the DT scenarios the periscope is used to build a visual picture and identify the priority contact.

C2. *Nodal task network metrics*

The metrics describing tasks relating to the priority contact during the DT scenarios do not stand out (see table 15), however the combined emission and receptions for the three tasks related to the priority contact, are together the highest numbers across all tasks across the three scenarios. This highlights the importance of the priority contact, but also that the tasks completed to track the contact are disparate.

Table 15. Nodal task network metrics INSO and DT

The INSO scenarios are the most perilous in terms of other vessel avoidance; therefore having an accurate, up-to-date, tactical picture is critical. During a RTPD passive sonar is the primary instrument used as the submarine is too deep to raise visual sensors and active transmissions might give away the position of the submarine. The first tasks involve detection of contacts on the hull or bow sonar array. A tactical picture is then required to be generated using sonar, this includes designating contact IDs and sending bearing cuts from the sound room to the picture room; classifying contacts, whilst also generating speed and course estimates using the tools available in the sonar suite. Such information is used to generate contacts solutions concerning the likely behaviour of the vessel.

The contact solutions that have been generated can constantly be refined as updated information (e.g. speed, bearing and course) is provided. In the RTPD task networks, the sonar tasks completed on the bow and hull sonar arrays are parallel, in essence these are the same tasks, although their completion might be slightly different (e.g. due to different sensor capabilities). The sociometric status of sonar tasks (e.g. detection and building sonar picture) are the highest of all tasks during the RTPD scenario and have equivalent values of the periscope related tasks during the INSO scenarios (e.g. raising periscope and building visual picture).

In the analysis of the task networks, parallel sonar tasks (i.e. the same task using different sonar arrays) are grouped into one, however for descriptive purposes in the RTPD scenarios they have been separated. Across all three scenarios, the command team is required to generate solutions and refine solutions to build a tactical picture. The sociometric status of refining solutions is the highest of all scenarios in the RTPD scenarios, potentially due to the fact that the sonar picture generated when deep is highly ambiguous and so constant refinement of solutions is required.

A number of other tasks are completed across the three scenarios (see tables 14 and 15). Firstly, steering the submarine, this occurs for three primary purposes; to keep the submarine safe (e.g. away from contacts), to complete mission objectives (e.g. navigate inshore), to clear stern arcs and ranging of contacts. Clearing stern arcs involves steering the submarine in a different direction, changing the coverage of the sonar arrays to compensate for any blind spots (i.e. in the stern arcs). It is a safety routine completed during a RTPD, but is not completed during DT (as submarine is at safe depth) or during INSO (as the periscope is used to stay safe). During a RTPD, clearing stern arcs has a high sociometric status and has one of the highest betweeness values ofall tasks (see table 14). The submarine will not RTPD (and use surface sensors) unless stern arcs have been cleared, as there may be vessels behind the submarine that had have not been detected. In the RTPD scenarios final reports are completed, this is a drill that is completed in which the parameters of all known contacts held are read aloud to the crew – along with any priority contacts (e.g. closing or threatening). The betweeness value of completing final reports is high (see table 14), similarly to clearing stern arcs, this task is important as it provides a final summation of the sonar picture prior to RTPD.

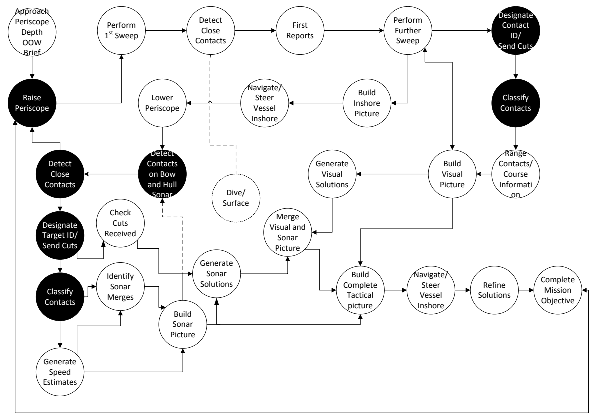

Figure 4b. Task network (INSO)

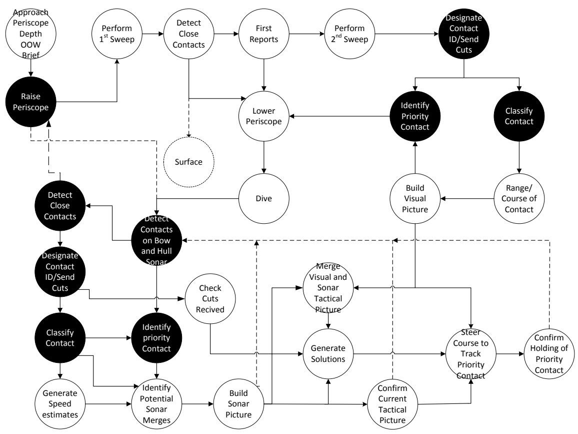

Figure 4c. Task network (DT)

C3. Effect of task demand

It is worth noting that the team of expert submariners completed all of the scenarios successfully. This means that all contacts were identified, correctly classified, and tracked. The only substantive difference in performance was the time taken to complete each scenario, which is show in table 16.

TABLE 16. Scenario completion times

Scenario	Low Demand	High Demand
RTPD	16m 51s	26m 12s
INSO	37m 11s	41m 7s
DT	27m 32s	36m 35s

As table 16 shows, lower demand tasks were completed quicker than the higher demand tasks, although the difference was markedly less for INSO. Table 17 shows that generally more tasks were completed in higher demand condition, although the difference was marginal for the DT scenario.

TABLE 17. Number of tasks completed in the three scenarios

Scenario	Low Demand	High Demand
RTPD	44	72
INSO	72	96
DT	87	90

D. Network Archetypes

A network can be defined as a group or system of interconnected people or things that facilitates the exchange of data and/or information to achieve higher goals [23, 24]. Examination of network archetypes as an indicator of team performance has been successfully completed in many domains [7, 18, 20, 23-25]. Network archetypes can show where bottlenecks in the system might exist, how resilient the system is and where the break points in the system might be [7, 13, 14, 23]. Four classic team structures have been defined as chain, Y, circle and wheel [26]. These structures have implications for the performance of team members [13]. Such as the closeness to other members of the team, the volume of information they can receive and in turn their perception of responsibility and independence within the team. The Y structure has been shown to produce the best team performance in studies of command and control [13, 14, 25]. A mix of network archetypes were observable, indicating that communications between nodes occurred differentially depending on scenario type, demand and what the network was modelling (see table 18). Each of the networks were classified by two independent observers. This was undertaken by searching each of the networks visually for evidence of the archetypes. An overall 83 percent agreement was achieved [27]. The chain network archetype was predominantly apparent in the task networks (both high and low). This is perhaps not surprising as the chain network archetype is the most linear, this indicates that many of the tasks cannot be completed until a preceding task has been completed (e.g. speed estimates may be required to generate sonar solutions).

The social and information networks are primarily a mixture of circle and star network archetypes and differ depending on scenario type and load. This indicates that the networks may vary depending upon what type of information is being communicated and which operator is required to pass each piece of information. The star network facilitates the transition of information from one node to many others (and vice versa). For example, the OOW disseminates commands to the entire crew. In response, the crew provides information that the OOW uses to compile a complete tactical picture. In terms of the information networks, the star archetype supports the integration of information to one single source (e.g. speed, course, range and bearing provide knowledge of a contact).

Table 18. Classification of network archetypes

Scenario	**RTPD**						**INSO**						**DT**					
Network	Social		Info		Task		Social		Info		Task		Social		Info		Task	
Demand	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
Archetype																		
Chain					*	*				*	*	*					*	*
Circle	*	*	*	*			*	*	*	*	*	*	*	*	*	*	*	*
Y		*			*	*	*				*	*			*		*	*
Star	*	*	*	*			*	*	*	*			*	*	*	*		

At present, the classification of the network archetypes and their hybrids is purely descriptive in nature. It is however, interesting to identify the patterns of networks in an expert submariner team for future comparison purposes. The structures do appear to be remarkably similar across the scenarios, so they may be invariant. Only when more teams are examined will be know this for sure. Future studies could explore structural changes in the team and see if this results network archetype changes.

IV. General discussion

The current work aimed to provide a comprehensive understanding of submarine command team functionality across a variety of operations routinely completed by submariners. It is clear that safe submarine operation is complex, requiring the integration of vast amounts of data from different instruments by different operators [4-9]. A striking observation is how different the composition of the networks can be depending upon scenario type and demand. The global network metrics clearly highlight that the social interactions, information transition and focus of tasks is very different depending on the particular operation being completed. Understanding such differences is critical as submarines are increasingly being required to operate in waters with higher volumes of contacts [16]. Examination of the network archetypes reveals that the chain archetype is only within the task networks. This network archetype may be seen as the least resilient, due to the fact that a break in the chain would effectively terminate information transition [14,15, 23]. The fact that the social and information networks are primarily examples of circle and star archetypes indicates that there is clear integration of information from disparate sources (e.g. operators and instruments). The conception of submarine command and control in the form of social, information and task networks is consistent with the distributed cognition approach [28, 29, 30]. This lends support to previous work offering a similar perspective on submarine command teams and also justified the methods employed in the current work [6-9, 17]. The current work offers insight into how the integration of information to inform a tactical picture changes across three different scenario types, building upon previous submarine command team studies which examined one task type or one scenario type [5-9, 17].

The OOW is a central figure in the command team, with high sociometric status and involvement in the greatest number of tasks. This supports previous work that reports the CO the only person within the team who has complete awareness of the tactical picture [5]. The high importance of OOW during RTPD scenarios has previously been demonstrated [7], however the current work has revealed similar patterns across all three scenarios. A positive of this role is that the majority of the procedural tasks (e.g. data analysis) are distributed across the command team and the information received by the OOW has been filtered (by OPSO and SOC) so that only relevant information is passed. However, the demand placed on the OOW across all scenario types has the potential to be problematic. The OOW is the central node in the star network archetype, if this node was to be removed, the impact on the functionality of the command team may be negative [14, 15]. A change in policy (e.g. less hierarchical command team structure) may facilitate a distribution of the responsibilities OOW has to other members within the command team. If the OOW is required to shoulder the large burden of tactical decisions, then it is crucial that information is presented to them in a fashion that is intuitive so that cognitive capacity is not wasted by having to interpret and/or integrate incoming information.

The volume of information passed between SOC and OPSO is great. The strength of such a connection is due to the fact that the sonar picture is passed to the picture compilers via this route as exemplified in previous work [6, 7]. OPSO and SOC are required to communicate with their operators (TMAs and SOPs respectively) to attain information required for building a sonar picture and generating solutions using sonar data. The generation of accurate solutions relies on information processed in the sound room (e.g. speed estimates) and is an example of how in a sociotechnical system. No one individual can complete the entirety of tasks required for a particular operation but rather multiple individuals and teams (e.g. picture room and sound room) must work together in pursuit of a common goal [6, 28, 29]. The benefits of a reliance on SOC and OPSO is they act as information filters (to OOW), whilst also quality checking the work of operators and adequately delegating workload. A potential problem however, is that OPSO and SOC are located in different rooms, and quite a distance away from each other in the control room. If the connection between OPSO and SOC was to be broken then the passage of sonar information to the picture room would degrade, almost completely, potentially resulting in degraded team performance [11, 12].

A number of solutions may alleviate the weight of information transition placed upon OPSO and SOC. Firstly, positioning OPSO and SOC next to each other in the control room may reduce the amount of communication required between such operators and increase the quality of data transition. Secondly. Allowing a greater connectivity between the TMAs and SOPs, may reduce the burden placed upon SOC and OPSO for routine data transition (e.g. speed estimates) and allow a focus on key information (e.g. new contacts and priorities). The greater connectivity between the TMAs and SOPS may be facilitated by a new control room configuration (e.g. placing TMAs and SOPS next to each other) or a change in policy encouraging such communication, along with improved architecture (a communication channel specifically between these operators). OPSO experiences a similar level of information transition load as OOW, as when the focus of the data integration is visual, OPSO simply communicates more with PERI and less with SOC. New control room configurations and interfaces may have the potential to reduce the load placed on OPSO, in a similar fashion outlined above for OOW [5].

The volume of communications across the entire command team dramatically increased during the high demand scenarios – this is not surprising as there is more information to pass (e.g. more contacts to manage). However, if scenario demand continued to increase the volume of communications may rise to a point where due to capacity limitations (i.e. speed of speech) it is simply impossible to convey more information [16]. To overcome such issues, it may be possible to design a system that facilitates the visual transition and receipt of information, reserving verbal communication only for key tasks (e.g. priority contacts). The type of information being passed across all scenarios remained relatively consistent and typically related to the behaviour of contacts (speed, bearing, range etc.), despite the primary source of such information changing (e.g. visual vs. sonar). This implied that the performance of the whole team may be improved by having the ability to communicate with everyone. This is supported by the fact the most common social and information network archetypes across all scenarios were circle and star, the latter of which is hypothesized to be the most resilient [14, 15]. The information being utilized and the tasks being completed by many operators relates to the same thing, namely gaining information concerning the parameters of a contact and using such data to predict future contact behaviour. The generation of a multi-purpose interface, that facilitates the display of contact parameters from sonar and visual data, along with TMA projections may have the potential to facilitate role merging. The network metrics also reveal that the sociometric status of the TMAs and SOPS generally tends to be the lowest, indicating these roles may have the greatest potential for merging. A key driver in submarine command team operations is a reduction in manning, which role merging may feature alongside future work examining new physical layouts, supportive technologies, communication hardware, policies and new interfaces [7, 8].

The study of submarine command and control has also provided some insights into the EAST method as a byproduct of the investigation. At present the focus has been on the humans in the command team, but future analyses should also incorporate the non-human actors in the team [30, 31], particularly as some of the work may be passed to machines or new, non-verbal, communications are used. The models themselves are based on observed activity (with SME verification), which means they useful, but not perfect [7]. As they represent normal behavior of one expert team, more teams would have to be studied to understand performance variability. The models can be used to consider what future ways of working might look like [7] and what might go wrong [31]. Finally, collecting and analyzing data from live performance of teams is extremely time consuming and resource intensive. Once the data has been collected however, it can be put to many uses such as verbal protocol analysis, classifications of team and individual activities, as well as modeling of team performance.

Finally, it is worth noting that the studies were undertaken using a simple submarine simulation that allows some control over the scenario, activity setting and observation. Whilst the various network patterns described are likely to be a reasonable facsimile of operations at sea, validating those patterns at sea would be beneficial.

V. Conclusions

The performance of the submarine command team across all scenarios was exemplary, accomplishing mission objectives across all scenarios with a focus on submarine safety [3]. Although the submarine control room is in a high state of evolution it does not mean that it cannot be improved upon [7]. There is a constant drive for submarines to increase capabilities, whilst operating in difficult conditions and utilizing a wider array of complex instruments to facilitate operations [3-5]. For this to be possible a thorough evaluation of submarine control room design and command team performance is required – including evaluations of optimizing new technologies, layouts, ways of working and interfaces. The current work provides a baseline describing how submarine command teams currently function – offering insight into future ideas for improvement, providing a baseline for comparison whilst also providing a methodological template for future research in this domain.

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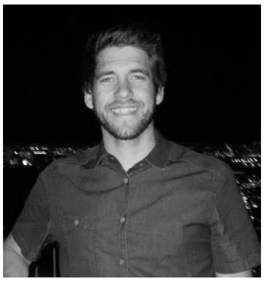

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