Land Ahoy! – Understanding submarine command and control during the completion of inshore operations

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Abstract

Objective: Use multiple command teams, to provide empirical evidence for understanding submarine control room performance when completing higher and lower demand Inshore Operation (INSO) scenarios.

Background: The focus of submarine operations has changed, submarines are increasingly required to operate in costal littoral zones. However, submarine command team performance during INSO is not well understood, particularly from a sociotechnical perspective.

Method: A submarine control room simulator was built. The creation of networked workstations allowed a team of 9 operators to perform tasks completed by submarine command teams during INSO. The Event Analysis of Systematic Teamwork (EAST) method was used to model the social, task and information networks and describe command team performance. 10 teams were recruited for the study, affording statistical comparisons of how command team roles and level of demand affected performance.

Results: Indicated that the submarine command team are required to rapidly integrate sonar and visual data as the periscope is used, periodically, in a ‘duck-and-run’ fashion, to maintain covertness. The fusion of such information is primarily completed by the Operations Officer (OPSO), with this operator experiencing significantly greater demand than any other operator.

Conclusion: The OPSO was a bottleneck in the command team when completing INSO, experiencing similar load in both scenarios. Suggesting the command team may benefit from data synthesis tasks being more evenly distributed within the command team.

Application: The work can inform future control room design and command team ways of working by identifying bottlenecks in terms of information and task flow between operators.

Key words: Submarine, Team Work, Communications, Networks

Précis: The current work examines submarine command team performance during the completion of Inshore Operations from a sociotechnical perspective. The recruitment of multiple command teams has afforded statistical investigation of performance, providing empirical evidence for understanding the functionality of submarine control rooms.

Introduction

Submarine Command and Control: Inshore Operations

Submarine command teams exhibit a high state of maturity in terms of functionality and capability, but this does not mean that improvements cannot be made (Stanton, 2014; Stanton, & Bessell, 2014). To operate effectively, a submarine command team is required to integrate data from a range of sensors, requiring the interaction of numerous command team members (Dominguez, Long, Miller, & Wiggins, 2006; Huf, Arulampalam, Masell, Tynan, Brown, Manning, 2004). In recent years, the focus of submarine operations has changed, submarines are increasingly required to operate in costal littoral zones instead of the deep ocean. The missions range from reconnaissance, to costal protection and scientific research (Duryea, Lindstrom, & Sayegh, 2008; Bateman, 2011; Stone, Caird-Daley, & Bessell, 2009). A change in submarine operations (e.g. increased costal deployment) is likely to have an effect on the control room teamwork. Understanding how instruments, sensors and interfaces facilitate the generation of a tactical picture during ‘typical’ deep sea operations is a challenge due to the complexity of sociotechnical systems (Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015; Loft, Sadler, Braithwaite, & Huf, 2015; Huf, Arulampalam, Masell, Tynan, Brown, Manning, 2004; Stanton, & Bessell, 2014). An even greater challenge is understanding how the functionality of a submarine control room changes due to different operational demands, as inshore operations (INSO) have, to the authors knowledge, not been investigated previously.

Operating in coastal waters presents a number of challenges, most notably the waters are shallow, creating a complex underwater environment with poor sound propagation which reduce sonar detection capabilities (Glosny, 2004). Coastal regions, particularly those that are populated, typically have cargo vessels, fishing vessels and pleasure crafts operating, which increase complexity for the control room team (Holt, Noren, Veirs, Emmons, & Veirs, 2009). The demand placed on the command team will differ depending on the volume of contacts in the area of operation. A priority for submarine command teams is to complete missions effectively whilst maximizing the safety of their own submarine and the safety of surrounding vessels (Jones, Steed, Diedrich, Armbruster, & Jackson, 2011). The manner in which safety is maximized is likely to be different for INSO compared to deep ocean regions and potentially when comparing higher and lower demand INSO. Successful decision making relies upon effective communication and teamwork, such processes can be the determining factor in terms of team workload rather than the work itself (Salas, Cooke, & Rosen, 2008; Stanton, 2011, Salas, Burke, & Samman, 2001; Carletta, Anderson, & McEwan, 2000). The manner in which a team is configured and how technology supports communication can influence their performance (Stanton, Rothrock, Harvey & Sorensen, 2015; Espevik, Johnsen, Eid, & Thayer, 2006).

Operating in areas with high volumes of contacts results in two main problems. Firstly, the sound propagation resulting from multiple contacts (potentially at similar bearings) makes detection, classification and ranging of vessels using passive sonar a challenge (Ogden, Zurk, Jones, & Peterson, 2011; Zarnich, 1999; Glosny, 2004). For example, biological contacts (e.g. a whale) have been demonstrated to increase their call amplitude in coastal areas where vessels are plentiful (Holt, Noren, Veirs, Emmons, & Veirs, 2009). Secondly, when navigating inshore, submarines typically operate at periscope depth. However, the periscope cannot constantly be raised, as the submarine needs to remain undetected (Bateman, 2011). This increases the potential for collisions with surface vessels, particularly as non-military vessels do not have the equipment or expertise to be aware of submarines operating in the area (Duryea, Lindstrom, & Sayegh, 2008; Champagne, Carl, & Hill, 2003). The requirement to avoid detection places the responsibility of avoiding collision on submarine command teams rather than surrounding vessels (Drumheller, & Benoit, 2004). Previous work has investigated submarine command team performance for the task of Returning to Periscope Depth (RTPD) (Stanton, 2014; Stanton, & Bessell, 2014). Such work highlighted a reliance on the use of passive sonar to generate a tactical picture and an understanding of where and when a safe RTPD could be accomplished (i.e. avoiding surface vessels), before periscope could be raised. This work did not examine how a command team completes INSO, where there is less reliance on passive sonar. Whilst the use of the periscope may facilitate safer operation, the requirement to remain undetected limits the time the periscope can be used (Zarnich, 1999; Glosny, 2004). Whilst other work has approached submarine command team performance from a sociotechnical perspective (e.g. Hunter, Hazen, & Randall, 2014), it has not examined INSO. A further limitation of previous studies is that only one command team was examined.

Whilst developing improved sonar sensor capabilities for the completion of inshore operations is continuing (e.g. Zarnich, 1999; Ogden, Zurk, Jones, & Peterson, 2011), to the authors knowledge an evaluation of submarine control room functionality from a sociotechnical perspective has not been completed. Therefore the purpose of this research was to gain an understanding of the control room teamwork for INSO. A further aim was to compare lower and higher demand, to understand the effects of civilian vessels operating in the local area.

Method

Participants

Participation in the study was voluntary. Participants were recruited opportunistically using posters and by directly contacting local groups with a maritime or military interest. A total of 10 teams of 8 individuals were recruited (80 participants in total). A total of 71 males and 9 females participated with an age range of 18-55 (Mean= 26.83, SD= 8.69) from a variety of backgrounds primarily including undergraduate students and graduate recruits from defence companies and organisations. One team were submariners from the British Royal Navy. The study protocol received ethical approval from the University of Southampton Research Ethics Committee (Protocol No: 10099) and MoDREC (Protocol No: 551/MODREC/14).

Equipment - The Submarine control room simulator

A submarine control room simulator was built to be representative of a currently operational Royal Navy (RN) submarine (for full description see Roberts et al., 2015). The control room had 9 networked workstations (see figure 1) including an Officer of the Watch station (OOW), an Operations Officer station (OpsO), a Sonar Controller station (SC), two Target Motion Analysis stations (TMA), two Sonar Operator stations (SOP), a Ship Control station (SHC) and a Periscope station (PERI). The simulator engine used was Dangerous Waters (DW), a software package developed by Sonalysts, which featured networked workstations for each of the roles. Two INSO scenarios were designed with Subject Matter Expert (SME) input and programmed in DW (see table 1). The movements of contacts was predetermined to be consistent across all teams and each scenario lasted approximately 45 minutes. The simulator was equipped with a comprehensive recording suite (e.g. web cameras and ambient microphones) which allowed the recording of all communications that occurred between operatives.

Figure 1. *The ComTET submarine control room simulator, with sound room on the left hand side and picture room on the right*

Design

The study employed a 2 x 8 mixed design. The independent variables were scenario demand (within subjects) and operator role (between subjects). Scenario demand was manipulated by the number of contacts detectable in the scenario and their behaviour (see table 1). The dependant variables included all communications that took place between operators within the command team and tasks completed.

Table 1. *Description of scenarios designed*

Name	**Demand**	**No. Contacts**	**Description**
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.

Procedure

Participants attended the submarine simulator for two full days (8am – 5pm). On the first day informed consent was attained and a simulator induction was completed, before team roles were randomly assigned. The morning of the first day (training) was spent watching a set of general submarine control room operation tutorials, whilst the afternoon was spent watching workstation specific tutorials and practicing tasks both individually and as a functional command team (see table 2 for a full description of tutorials). Each tutorial lasted approximately 45 minutes with regular breaks and refreshments provided between tutorials. Participants were encouraged to ask questions about their tasks and operation of their workstations as well as the communications protocol.

On the second day (testing) participants started with a refresher training scenario as a functional command team. Performance was assessed by experimenters to check that all tasks were being completed correctly in line with set criteria provided by SMEs (e.g. adequately detecting surrounding vessels, gaining solutions concerning surrounding vessels and steering the submarine safely to relevant courses and depths). After which the first scenario was begun – all recording devices were started and a verbal time stamp was read aloud for synchronization purposes. Each scenario started with an OOW briefing outlining the mission objectives (see table 1). To reduce order effects scenario presentation was counterbalanced across the 10 teams. Each team completed both scenarios, occupying the same positions in the command team. Once the mission objective had been achieved the end of the scenario was called and participants were provided with a short break before the start of the next scenario. At the end of the final scenario participants were provided with a full debrief and thanked for participating.

Table 2. *Description of tutorial training package*

Tutorial	Description	Purpose
Submarine Command	Introduction to the submarine simulator, the operator roles, the different sensors on board a submarine and the command structure within a submarine command team.	Develop basic understanding of what a submarine command team does, what type of data is received, what the operator roles are.
Introduction to bearing, speed, course and range	Describing the basics of bearing, speed range and course in relation to own submarine and to contacts that might be surrounding the submarine. Describing passive sonar and how information concerning speed can be derived from analysis of sound.	Develop an understanding that using passive sonar to create a tactical picture requires the interpretation of ambiguous information. Understanding that the only definite information is the bearing at which contacts are heard and that acoustic signature processing can provide ‘estimates’ of speed.
Military communication protocol	Detailing how military personnel are required to communicate with each other. A particular focus on clarity, conciseness and not interrupting communication flows. The structure of the command team was also outlined.	It was important to examine command team functionality with a level of fidelity that was comparable to operational procedures. The communication protocol in the military is clearly defined, it was important for operators to pass information in a manner comparable to operational teams
Anagram communication game (3 game trials)	This required participants to solve anagrams (analogous to processing data), then pass the words around the command team in a structured fashion (using standard verbal protocol) and then linking up the words to create a sentence (analogous to creation of a tactical picture).	This brought together the morning training session. It allowed participants to understand that they may all be completing different tasks and contributing different pieces of information to facilitate the generation of an overall tactical picture. It allowed participants to practice operating as a command team without the complexities of the domain.
Workstation tutorial (Sonar, TMA, Periscope and SHC)	A complete description of all workstation interfaces. What the fundamental task requirements of each operator in the command team are and how they should interact with the interfaces to complete their specific duties within the command team.	To develop an understanding of the particular tasks completed by each individual within the command team. This tutorial was completed very much at the level of the individual with a focus on manipulating the interface for procedural task completion. Examples include how to spot a contact on sonar, how to listen to a contact, how to designate a tack ID on sonar.
Practice workstation free play	Workstation specific training scenarios were developed to encapsulate all tasks participants would encounter. Participants completed scenarios individually, with the rest of the command team ‘auto crewed’. Experimenters answered any questions and guided participants through the completion of tasks they were unsure of.	Participants could speed up time. This allowed participants to work at their own pace. The purpose of this part of the training was to allow participants to complete all of the task that they would be expected to complete in the command team, without command team pressures. Participants could restart scenarios multiple times and speed up time, allowing a focus on the tasks and procedures they felt needed the most attention.
Command team tutorial	A detailed description of how the tasks completed by each individual operator (and the information derived) should be shared across the command team to facilitate the generation of a complete tactical picture.	This part of the tutorial brings together the communication game, which taught participants the command structure and communication protocol. Instead of using anagrams as data, participants were now made aware of the tasks and data they were responsible for and which members of the command team need this information to generate a tactical picture.
Practice INSO scenario completion	Participants completed shortened versions of the 2 scenarios (INSO) that they would be expected to completed during testing. The scenarios were completed at least twice. Participants were given guidance from the experimenters concerning how the tasks completed at individual workstations feed in to the global aims of the command team.	At this point participants were accomplished at completing the procedures and tasks at their own workstations. The final training session pulled together everything that had been learnt throughout the day. This included completing tasks at their workstation, passing relevant output (data) to members of the command team.

Analysis of data

A new shortened version of Event Analysis for Systemic Teamwork (EAST: Stanton, Barber & Harris, 2008) was used to analyse the data. This method has been presented in a previous study to model submarine command and control (Stanton, 2014). The framework has also been applied in other domains such as emergency services (Houghton, Baber, McMaster, Stanton, Salmon, Stewart, & Walker, 2006) and aviation (Stewart, Stanton, Harris, Baber, Salmon, Mock, & Kay, 2008; Stanton & Harvey, 2016). EAST examines complex sociotechnical systems using a network approach. The raw data from video and microphone recordings was used to generate three networks. Firstly, the social networks analyse communications taking place between 'agents' in the system. Secondly, information networks describe the information 'pieces' that different agents in the system use and communicate during task performance. Thirdly, task networks describe the relationships between tasks, their sequence and interdependences. These networks were processed using AGNA software (version 2.1.1 – a software program for computing the Social Network metrics). AGNA was also used to compute whole network metrics (e.g. density, diameter and cohesion) and nodal metrics (e.g. sociometric status and centrality of each node). A detailed description of all is provided in previous work (See Stanton, 2014). To examine the effect of scenario demand and operator role, network and nodal metrics were computed by completion of 2 x 8 mixed analyses of variances (ANOVAs). 2 x 14 repeated measures ANOVAs were conducted to examine the effect of scenario demand and information type on information node metrics. To examine differences in the frequency of task completion between scenarios of high and low demand 2 x 12 repeated measures ANOVAs were conducted. All significant main effects were examined by conducting post hoc pairwise comparisons. To account for multiple comparisons the

Bonferroni correction method was used. All statistical analysis was conducted using IBM SPSS v21.

Results

Social Network Analysis

The average frequency of communications between operators in the command team varied depending on command team role and scenario demand (see figure 2). OPSO and SOC had the largest volume of emissions and receptions of all operators. The overall composition of both networks is similar, however the volume of interactions between operators appears to increase during the high demand INSO scenario.

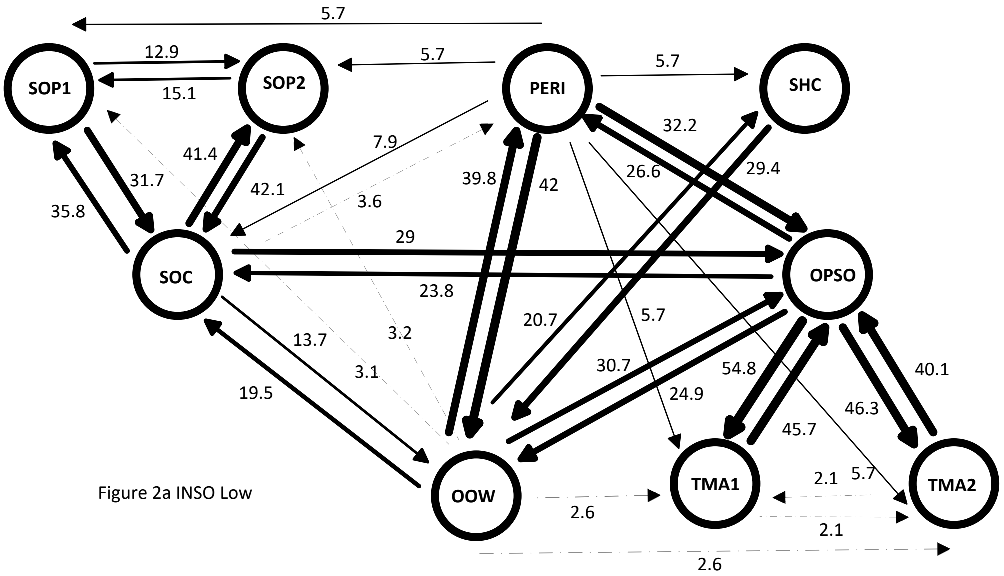

Figure 2a INSO Low

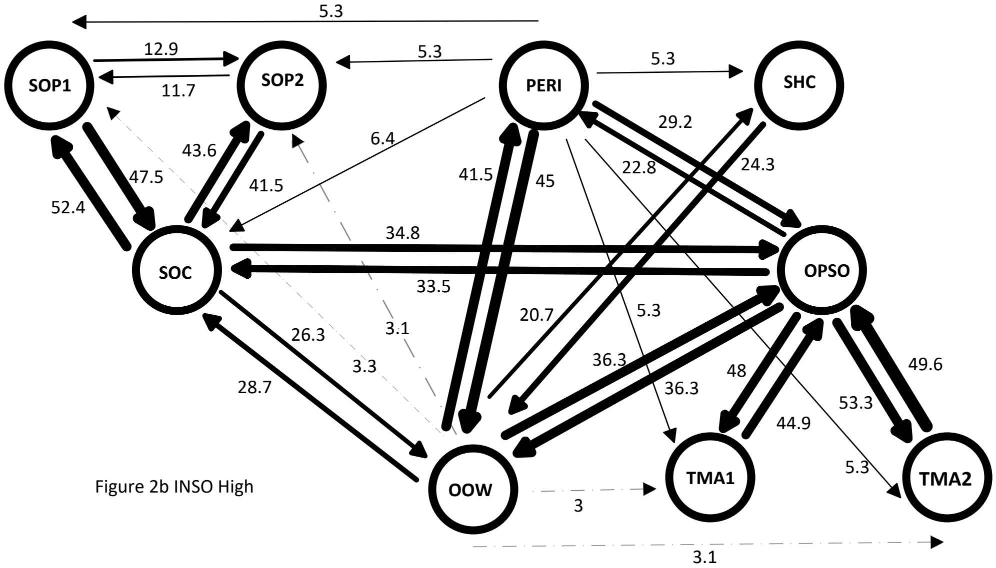

Figure 2b INSO High

Figure 2. *Social network diagrams for low and high demand INSO scenarios*

Whole Network Metrics

A non-significant trend was observed (t_{9} = -1.90, p = .09, *d* = 0.60) for an increase in the total number of emissions and receptions in the high demand INSO condition. No other statistically significant effects were observed, indicating the structure of the network remained relatively consistent in both higher and lower demand conditions (see table 3).

Table 3. *Social network Metrics for entire network INSO*

	INSO		**Effect of Demand (t Value)**
	Low	High	
Nodes	9	9	NA
Edges	31.30 ± 4.79	33.70 ± 3.37	1.23
Density	0.43 ± 0.07	0.47 ± 0.03	1.28
Cohesion	0.31 ± 0.07	0.33 ± 0.03	0.63
Diameter	3 ± 0.00	2.9 ± 0.32	1.00
Total Interactions	715.60 ± 118.04	800.70 ± 137.91	1.90^{t}

Nodal Metrics

Emissions

The total emissions of each node were significantly affected by scenario demand ($F_{1, 81} = 6.55$, $p < .05$, $\acute{\eta}_{p}^{2} = .07$) and operator role ($F_{8, 81} = 36.14$, $p < .01$, $\acute{\eta}_{p}^{2} = .78$). The interaction of scenario demand and role also statistically significantly affected total node emissions ($F_{8, 81} = 4.23$, $p < .01$, $\acute{\eta}_{p}^{2} = .80$). When examining the effect of scenario demand, post hoc analysis revealed emissions were statistically significantly higher ($p<.05$) in the high demand INSO condition than the low demand condition for OOW, OPSO, SOC and SOP1 (see table 4 and figure 2). When examining the effect of operator role post hoc analysis revealed that OPSO had statistically significantly (p<.05) more emissions than all operators. OOW, PERI and SOC had statistically significantly (p<.05) more emissions than all operators (except OPSO).

Table 4. *Social network metrics for individual nodes INSO low and high demand scenario*

		Emission		**Reception**		**Sociometric**		**Centrality**		**Betweeness**	
	N	Low	High	Low	High	Low	High	Low	High	Low	High
OOW	10	112.9 ± 31.6	133 ± 32.08	102.6 ± 21.68	125.7 ± 27.25	26.94 ± 6.13	32.34 ± 6.36	5.86 ± 0.37	5.94 ± 0.49	12.92 ± 5.43	14.75 ± 5.63
OPSO	10	172.2 ± 24.43	192.8 ± 26.64	176.3 ± 18.73	195.7 ± 32.11	43.57 ± 5.03	48.56 ± 7.23	5.79 ± 0.37	5.66 ± 0.23	18.15 ± 5.85	16.7 ± 3.76
SOC	10	88.2 ± 37.98	151.8 ± 38.91	93.6 ± 24.92	153.1 ± 40.43	22.73 ± 7.75	38.11 ± 9.49	5.29 ± 0.77	5.57 ± 0.35	11.98 ± 7.04	15 ± 4.85
SOP1	10	37.9 ± 7.96	54.1 ± 19.6	55.3 ± 24.67	66.2 ± 23.87	11.65 ± 3.52	15.04 ± 5.29	3.91 ± 0.12	3.99 ± 0.13	1.5 ± 4.74	0.07 ± 0.21
SOP2	10	61.2 ± 67.42	49.5 ± 22.23	70.6 ± 62.11	60.2 ± 24.24	16.48 ± 16.15	13.72 ± 5.6	4.19 ± 0.71	3.9 ± 0.16	5.1 ± 8.72	0 ± 0
TMA1	10	50.5 ± 21.38	44.5 ± 12.64	62 ± 19.34	54.9 ± 14.89	14.07 ± 4.97	12.43 ± 3.31	3.93 ± 0.08	3.83 ± 0.12	1.8 ± 5.69	0 ± 0
TMA2	10	53 ± 31.19	49.7 ± 15.53	62.7 ± 27.65	59.4 ± 19.83	14.47 ± 7.25	13.64 ± 4.25	4.02 ± 0.26	4.05 ± 0.41	2 ± 5.66	0.17 ± 0.53
PERI	10	104.6 ± 50.79	105.3 ± 46.21	54.9 ± 28.25	63.9 ± 19.86	19.94 ± 9.42	21.15 ± 8.04	4.95 ± 0.57	5.21 ± 0.45	3.65 ± 2.8	3.62 ± 3.39
SHC	10	35.1 ± 21.29	24 ± 9.84	37.6 ± 18.48	25.6 ± 4.81	9.09 ± 4.66	6.2 ± 1.48	4.03 ± 0.6	3.82 ± 0.2	1.8 ± 4.73	0 ± 0
Effect of Demand (f Value)		6.55*		8.56**		7.95**		0.01		1.88	
Effect of Role (f Value)		36.14***		44.96***		43.25***		82.76***		43.69***	
Demand *Role (f Value)		4.23***		4.95***		4.84***		1.22		1.26	

Receptions

The total receptions of each node were significantly affected by scenario demand ($F_{1,\,81} = 8.56$, $p < .05$, $\acute{\eta}_p^2 = .10$) and operator role ($F_{8,\,81} = 44.97$, $p < .01$, $\acute{\eta}_p^2 = .82$). The interaction of scenario demand and role also statistically significantly affected total node receptions ($F_{8,\,81} = 4.95$, $p < .01$, $\acute{\eta}_p^2 = .33$). When examining the effect of scenario demand, post hoc analysis revealed receptions were statistically significantly higher ($p<.05$) in the higher demand INSO condition than the low demand condition for OOW, OPSO and SOC (see table 4 and figure 2). When examining the effect of operator role post hoc analysis revealed that OPSO had statistically significantly ($p<.05$) more emissions than all operators. SOC and OOW had statistically significantly ($p<.05$) more receptions than all other operators (except OPSO).

Socio-Metric Status

The socio-metric status of each node was significantly affected by scenario demand ($F_{1,\,81} = 7.95$, $p < .05$, $\acute{\eta}_p^2 = .09$) and operator role ($F_{8,\,81} = 43.23$, $p < .01$, $\acute{\eta}_p^2 = .81$). The interaction of scenario demand and role also statistically significantly affected total node receptions ($F_{8,\,81} = 4.84$, $p < .01$, $\acute{\eta}_p^2 = .32$). When examining the effect of scenario demand, post hoc analysis revealed that socio-metric status was statistically significantly higher ($p<.05$) in the higher demand INSO condition than the low demand condition for OOW, OPSO, SOC and SOP1. When examining the effect of operator role post hoc analysis revealed that OPSO had statistically significantly higher socio-metric status than all operators ($p<.05$). OOW and SOC but had statistically significantly ($p<.05$) higher socio-metric status than all operators (except OPSO).

Centrality

The centrality of each node was not statistically significantly affected by scenario demand ($F_{1,\,81}$ = 0.01, p > .05) or the interaction between scenario demand and role ($F_{8,\,81}$ = 1.22, p > .05) but was significantly affected by operator role ($F_{8,\,81}$ = 82.76, p < .01, $ή_p^2$ = .89). When examining the effect of operator role post hoc analysis revealed that OOW had statistically significantly (p<.05) higher centrality than all operators (except OPSO). OPSO had statistically significantly greater centrality than all operators (except OOW and SOC). SOC and PERI had statistically significantly (p<.05) higher centrality than all other operators.

Betweenness

The betweeness of each node was not statistically significantly affected by scenario demand ($F_{1,\,81}$ = 1.87, p > .05) or the interaction between scenario demand and role ($F_{8,\,81}$ = 1.26, p > .05) but was significantly affected by operator role ($F_{8,\,81}$ = 43.69, p < .01, $ή_p^2$ = .81). When examining the effect of operator role post hoc analysis revealed OOW, OPSO and SOC had statistically significantly (p<.05) higher betweenness than all operators.

Information Network Analysis

The structure of the information networks is relatively consistent in both low and high demand INSO scenarios with ‘contact’, ‘bearing’, ‘periscope’ and ‘solution’ the most connected information pieces (see figure 3). The volume of emissions from most information pieces increased in the high demand INSO scenario although differences in relationships can be observed.

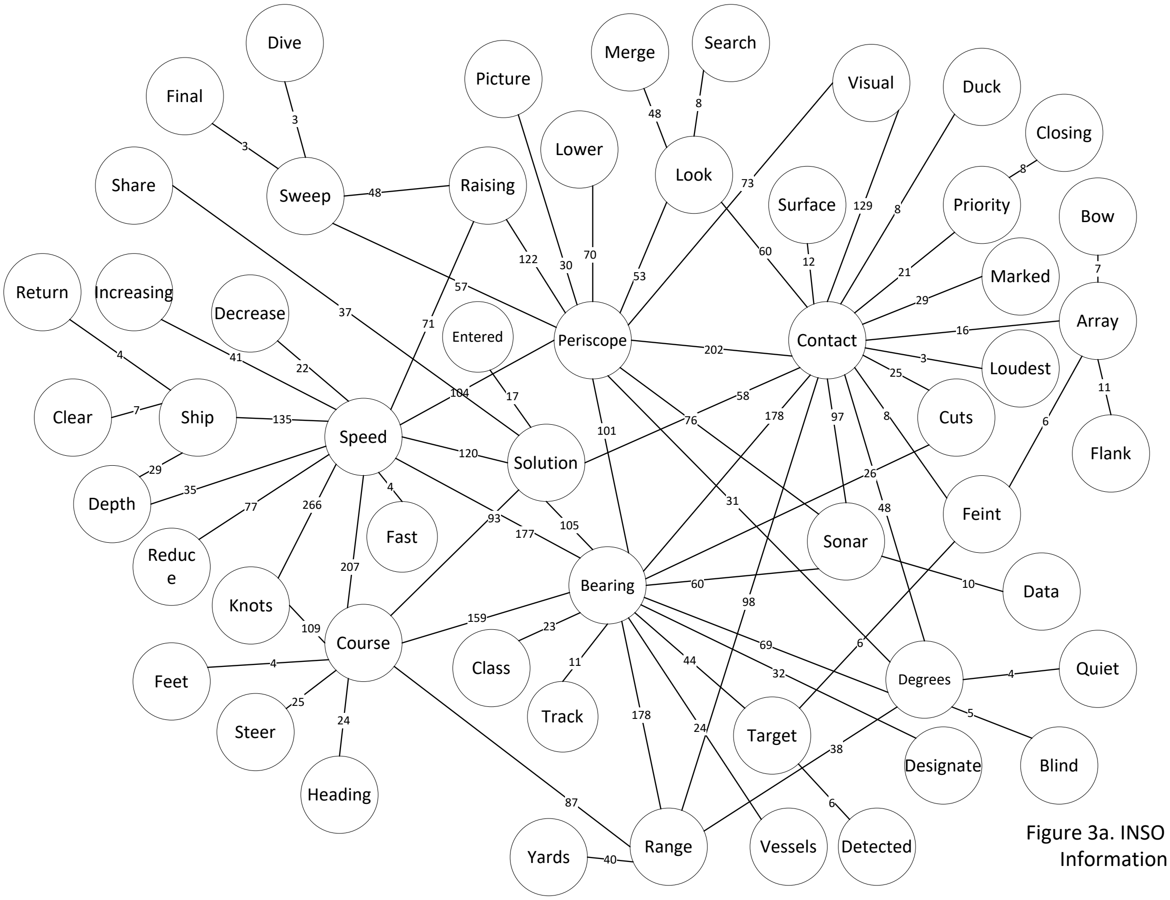

Figure 3a. INSO low demand Information network

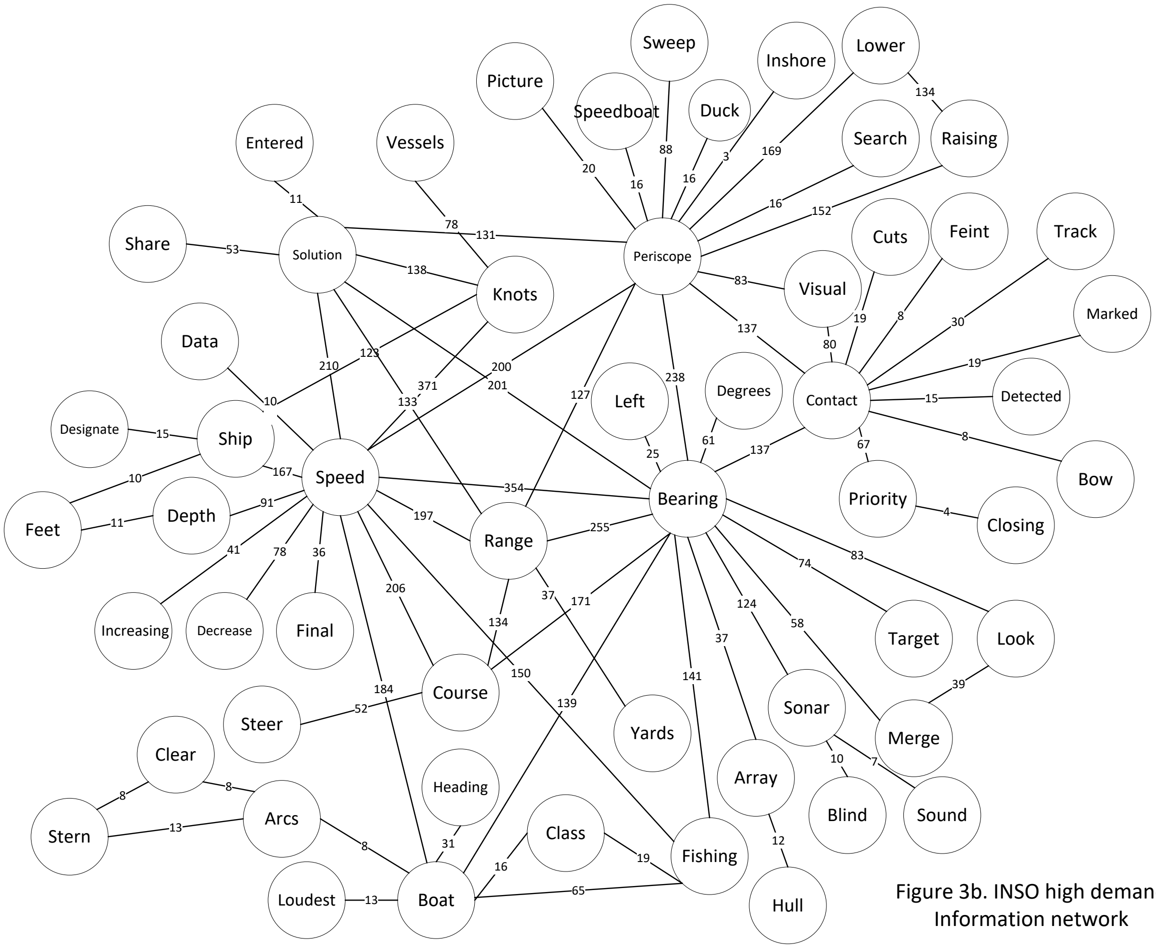

Figure 3b. INSO high demand Information network

Figure 3. *Information network diagrams for low and high demand INSO scenarios*

Whole Network Metrics

The total number of edges was statistically significantly ($t_9 = 2.76$, p < .05, *d* = 0.48) higher in the high demand condition. Total emissions ($t_9 = 3.01$, p < .05, *d* = 0.80) were statistically significantly higher in the high demand condition (see table 5). This indicates that the volume of information passed between operators and connectivity between information was greater in the high demand INSO scenario.

Table 5. *Information network Metrics for entire network INSO*

	INSO		Effect of Demand (t Value)
	Low	High	
Nodes	45.90 ± 5.70	48.80 ± 4.68	1.60
Edges	738.20 ± 313.34	932.40 ± 414.33	2.67*
Density	0.56 ± 0.24	0.62 ± 0.22	1.56
Cohesion	0.38 ± 0.11	0.43 ± 0.15	1.73
Diameter	2.90 ± 0.57	3.0 ± 0.67	0.55
Total Emissions	2322.40 ± 1154.49	4256.40 ± 2212.99	3.01*

Nodal Metrics

Emissions

The total emissions of each node were statistically significantly affected by scenario demand ($F_{1, 126} = 52.45$, $p < .01$, $ή_p^2 = .29$) and concept type ($F_{13, 126} = 8.68$, $p < .01$, $ή_p^2 = .47$). A statistically significant interaction ($F_{13, 126} = 1.90$, $p < .05$, $ή_p^2 = .16$) between scenario demand and scenario type was also observed. Post hoc analysis revealed emissions were statistically significantly higher ($p<.05$) in the high demand INSO condition than the low demand condition. Post hoc analysis revealed that the total emissions of bearing was statistically significantly ($p<.05$) higher than look, merge, priority, sonar, sweep, depth and visual. Course had statistically significantly more emissions ($p<.05$) than merge, priority and depth. Periscope had statistically significantly ($p<.05$) more emissions than look, merge, priority, sonar, sweep, depth and visual. Speed had statistically significantly ($p<.05$) more emissions than all concepts except bearing, course, periscope and range (see table 6 and figure 3).

Table 6. *Information network metrics for individual nodes INSO low and high demand scenario*

	Emission		**Reception**		**Sociometric**		**Centrality**		**Betweeness**	
	Low	High	Low	High	Low	High	Low	High	Low	High
Bearing	199.40 ± 98.86	345.00 ± 174.77	199.40 ± 98.86	345.00 ± 174.77	9.02 ± 4.42	14.61 ± 7.67	30.09 ± 3.52	32.98 ± 4.33	144.07 ± 94.51	152.45 ± 101.97
Contact	168.20 ± 172.89	164.30 ± 86.86	168.20 ± 172.89	164.30 ± 86.86	7.64 ± 7.80	6.94 ± 3.84	30.11 ± 4.15	31.39 ± 4.67	158.40 ± 92.92	128.26 ± 112.22
Course	145.20 ± 54.42	227.17 ± 77.44	145.20 ± 54.42	227.17 ± 77.44	6.64 ± 2.60	9.47 ± 3.80	27.72 ± 4.61	29.85 ± 4.57	80.08 ± 59.68	65.53 ± 55.17
Look	72.90 ± 36.67	115.82 ± 83.40	72.90 ± 36.67	115.82 ± 83.40	3.30 ± 1.70	4.91 ± 3.62	25.96 ± 4.42	28.71 ± 3.97	50.59 ± 45.44	63.37 ± 74.71
Merge	42.65 ± 33.52	79.60 ± 74.43	42.65 ± 33.52	79.60 ± 74.43	1.95 ± 1.53	3.42 ± 3.36	23.46 ± 3.83	25.18 ± 4.84	18.01 ± 17.14	41.27 ± 62.06
Periscope	169.91 ± 170.74	268.20 ± 199.97	169.91 ± 170.74	268.20 ± 199.97	7.71 ± 7.78	11.33 ± 8.92	28.52 ± 4.92	31.60 ± 4.74	88.74 ± 54.60	119.40 ± 66.94
Priority	34.12 ± 41.89	88.30 ± 87.44	34.12 ± 41.89	88.30 ± 87.44	1.56 ± 1.82	3.79 ± 4.08	23.14 ± 4.11	25.39 ± 5.78	20.42 ± 45.12	32.36 ± 65.46
Solution	97.16 ± 49.12	194.20 ± 88.86	97.16 ± 49.12	194.20 ± 88.86	4.45 ± 2.48	8.34 ± 4.31	25.46 ± 4.23	29.84 ± 4.18	36.50 ± 22.67	69.76 ± 61.68
Sonar	72.50 ± 98.26	118.80 ± 143.53	72.50 ± 98.26	118.80 ± 143.53	3.27 ± 4.47	5.15 ± 6.50	25.14 ± 5.42	27.05 ± 3.49	39.99 ± 43.62	40.27 ± 51.52
Speed	194.70 ± 59.60	369.60 ± 144.32	194.70 ± 59.60	369.60 ± 144.32	8.88 ± 2.90	15.64 ± 6.57	29.20 ± 4.45	32.91 ± 4.87	120.69 ± 66.04	115.74 ± 79.44
Sweep	49.60 ± 27.76	100.32 ± 85.92	49.60 ± 27.76	100.32 ± 85.92	2.29 ± 1.34	4.22 ± 3.82	24.26 ± 2.71	26.43 ± 3.35	19.52 ± 9.03	29.14 ± 25.03
Depth	40.17 ± 44.85	81.04 ± 79.59	40.17 ± 44.85	81.04 ± 79.59	1.86 ± 1.93	3.35 ± 3.18	22.11 ± 5.06	25.46 ± 5.90	16.12 ± 37.11	25.36 ± 28.98
Range	133.03 ± 75.26	215.34 ± 93.48	133.03 ± 75.26	215.34 ± 93.48	6.00 ± 3.45	9.01 ± 4.06	26.91 ± 3.58	29.82 ± 4.16	51.79 ± 32.89	60.56 ± 39.95
Visual	74.40 ± 49.67	87.80 ± 64.78	74.40 ± 49.67	87.80 ± 64.78	3.45 ± 2.27	3.77 ± 3.03	25.51 ± 3.00	27.98 ± 3.62	41.52 ± 40.00	43.05 ± 19.44
Effect of Demand (f Value)	52.45***		52.45***		38.69***		45.07***		1.78	
Effect of Concept (f Value)	8.68***		8.68***		7.73***		5.07***		7.57***	
Demand*Concept (f Value)	1.90*		1.90*		1.61^{t}		.31		.70	

Receptions

The total receptions of each node were statistically significantly affected by scenario demand ($F_{1, 126}$ = 52.45, p < .01, $ή_p^2$ = .29) and concept type ($F_{13, 126}$ = 8.68, p < .01, $ή_p^2$ = .47). A statistically significant interaction ($F_{13, 126}$ = 1.90, p < .05, $ή_p^2$ = .16) between scenario demand and scenario type was also observed. Post hoc analysis revealed receptions were statistically significantly higher (p<.05) in the high demand INSO condition than the low demand condition. Post hoc analysis revealed that the total receptions of bearing was statistically significantly (p<.05) higher than look, merge, priority, solution, sonar, sweep, depth and visual. Course had statistically significantly more receptions (p<.05) than merge, priority and depth. Periscope had statistically significantly (p<.05) more receptions than look, merge, priority, sonar, sweep, depth and visual. Speed had statistically significantly (p<.05) more receptions than all concepts except bearing, course, periscope and range (see table 6 and figure 3).

Socio metric status

The socio metric status of each node was statistically significantly affected by scenario demand ($F_{1, 126}$ = 38.69, p < .01, $ή_p^2$ = .24) and concept type ($F_{13, 126}$ = 7.73, p < .01, $ή_p^2$ = .44). No statistically significant interaction between scenario demand and scenario type was observed, although a non-significant trend was observed ($F_{13, 126}$ = 1.61, p = .09). Post hoc analysis revealed socio metric status was statistically significantly higher (p<.05) in the high demand INSO condition than the low demand condition. Post hoc analysis revealed that bearing had statistically significantly (p<.05) higher socio metric status than all information pieces except contact, course, periscope, speed and range. Course had statistically significantly (p<.05) higher socio metric status than merge, priority and depth. Periscope had statistically significantly (p<.05) higher socio metric status than look, merge, priority, sonar, sweep, depth and visual. Speed had statistically significantly ($p<.05$) higher socio metric status than look, merge, priority, solution, sonar, sweep, depth and visual.

Centrality

The centrality of each node was statistically significantly affected by scenario demand ($F_{1,\,126} = 45.07$, $p < .01$, $ή_p^2 = .26$) and concept type ($F_{13,\,126} = 5.02$, $p < .01$, $ή_p^2 = .34$). Post hoc analysis revealed centrality were statistically significantly higher ($p<.05$) in the high demand INSO condition than the low demand condition. Post hoc analysis revealed that bearing had statistically significantly ($p<.05$) higher centrality than merge, priority, sonar, sweep and depth. Contact had statistically significantly ($p<.05$) higher centrality than merge, priority, sweep and depth. Periscope had statistically significantly higher ($p<.05$) centrality than merge, priority and depth. Speed had statistically significantly ($p<.05$) higher centrality than merge, priority, sonar, sweep and depth.

Betweeness

The betweeness of each node was statistically significantly affected by concept type ($F_{13,\,126} = 7.92$, $p < .01$, $ή_p^2 = .45$). Post hoc analysis revealed that bearing and contact had statistically significantly ($p<.05$) higher betweeness than all concepts except periscope and speed. Periscope had statistically significantly ($p<.05$) higher betweeness than merge, priority, sonar, sweep and depth.

Task network analysis

The type of tasks completed by the command team (same for high and low demand scenarios) centre around developing a tactical picture, to facilitate safe navigation inshore. The command team are required to complete tasks that utilise visual information and sonar information to best maximise submarine safety and covertness (see figure 4).

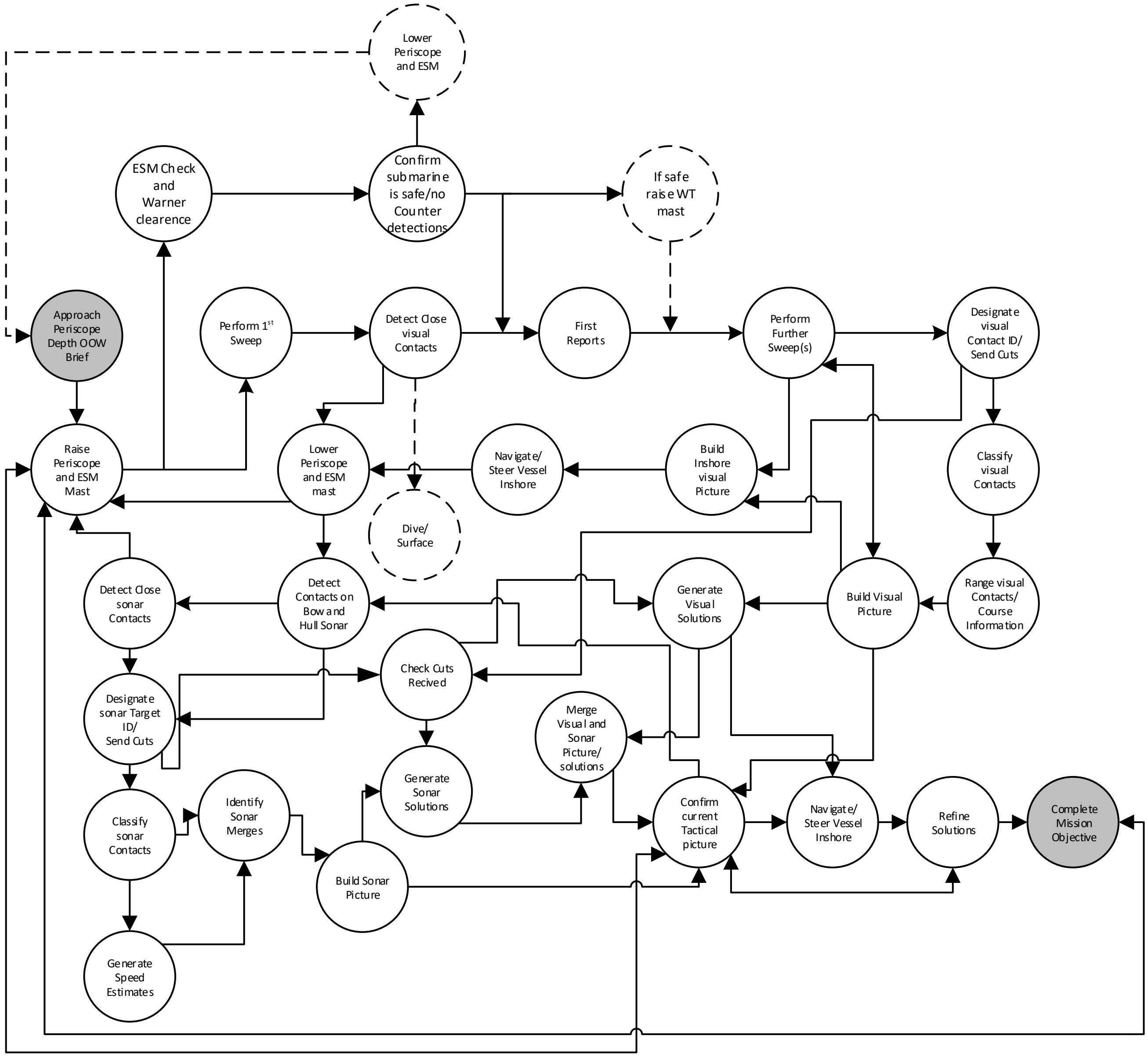

Fig. 4. *Task network diagrams for INSO low and high demand scenarios*

The tasks with the highest sociometric status were ‘raise periscope’, ‘perform 2nd sweep’ and ‘build visual picture’ (see table 7). Periscope was the primary instrument being used to safely navigate the submarine inshore. The periscope was also used to gather the relevant intelligence inshore – which was the mission objective. The verification of tasks networks by SMEs provided the basis for the completion of task frequency analysis.

Table 7 – *Task network metrics for individual nodes RTPD scenarios*

	Emission	**Reception**	**Sociometric**	**Centrality**	**Betweeness**
OOW brief	3	0	0.10	31.34	0.00
Raise Periscope	2	5	0.23	17.63	318.60
1st Sweep	1	1	0.06	16.59	125.60
Detect Close Visual	3	1	0.13	16.52	124.60
First Reports	1	2	0.10	13.84	110.80
2nd Sweep	3	3	0.19	15.34	206.20
Build Inshore Picture	1	2	0.10	22.64	11.43
Designate Visual	2	1	0.10	12.69	81.60
ESM check	1	1	0.06	16.59	164.00
Submarine safe	3	1	0.13	16.52	163.00
Raise WT mast	1	1	0.06	13.43	50.40
Lower Periscope	2	2	0.13	14.38	67.40
Surface	0	1	0.03	23.51	0.00
Classify visual contacts	1	1	0.06	11.42	34.17
Range/Course of visual	1	1	0.06	11.39	33.17
Build visual picture	4	2	0.19	14.79	121.17
Visual Solutions	2	0	0.06	24.28	0.00
Dive	1	2	0.10	14.27	53.50
Detect contacts sonar	2	3	0.16	18.71	223.30
Close sonar contact	2	1	0.10	17.63	45.50
Designate sonar contact	2	2	0.13	14.27	160.80
Classify Sonar Contacts	2	1	0.10	13.19	87.70
Speed estimates	1	1	0.06	12.02	0.00
Identify sonar merges	1	2	0.10	13.14	85.70
Check cuts received	2	2	0.13	14.21	90.53
Build Sonar Picture	2	1	0.10	13.10	84.70
Generate Solutions	1	2	0.10	13.94	49.03
Merge visual and sonar	1	2	0.10	14.21	75.03
Confirm tactical picture	3	5	0.26	18.61	301.57
Navigate/Steer vessel	0	3	0.10	32.45	0.00
Refine solutions	1	2	0.10	22.78	7.50
Complete Mission	2	0	0.06	27.78	0.00

The frequency of task completion was statistically significantly affected by scenario demand ($F_{1, 189} = 11.06$, $p < .01$, $\acute{\eta}_p^2 = .06$) and task type ($F_{20, 189} = 14.69$, $p < .01$, $\acute{\eta}_p^2 = .61$). A statistically significant interaction ($F_{20, 189} = 3.67$, $p < .01$, $\acute{\eta}_p^2 = .28$) between scenario demand and task type was also observed (see table 8). Post hoc analysis revealed the frequency of task completion was statistically significantly higher ($p<.05$) in the high demand condition than the low demand condition. The tasks of periscope sweep, detect visual, range visual, detect sonar, speed sonar, refine solutions and changing own submarine parameters were completed statistically significantly (*p*<.05) more than all other tasks (see table 8).

Table 8 – *Frequency of task completion INSO scenarios*

	INSO	
	Low	High
Detect Sonar Contacts	4.6 ± 1.35	7.8 ± 3.01
Designate Sonar Contacts	3.4 ± 1.58	5.4 ± 2.32
Classify sonar contacts	3.1 ± 2.18	6.1 ± 2.02
Sonar speed estimates	4.4 ± 3.44	7.1 ± 3.21
Sonar course estimates	1.7 ± 2.36	3 ± 3.65
Check cuts	1.3 ± 1.16	0.9 ± 1.29
Sonar Merges	0.3 ± 0.67	1.4 ± 1.07
Sonar Solution	2.8 ± 1.62	4.2 ± 2.25
Refine Solutions	4.4 ± 1.96	5.5 ± 5.1
Change Submarine parameters	7.3 ± 2.71	6.3 ± 0.95
Raise Periscope	2.8 ± 0.92	2.8 ± 1.03
Complete Sweep	4.3 ± 1.06	4.5 ± 1.35
Detect visual contacts	5.1 ± 2.13	5.2 ± 1.87
Designate visual contacts	4.7 ± 1.57	2.8 ± 1.62
Classify visual contacts	3.8 ± 2.57	3.9 ± 2.02
Range visual contacts	5.8 ± 1.69	4.6 ± 2.17
Course estimates of visual	2.3 ± 1.49	3.3 ± 2.21
Visual solutions	3.3 ± 1.64	1.5 ± 1.08
Merge visual and sonar	1.2 ± 1.23	1.5 ± 0.97
Clear stern arcs	0.1 ± 0.32	0.3 ± 0.48
Final reports	0.1 ± 0.32	0.1 ± 0.32
Effect of demand	11.06***	
Effect of task type	14.69***	
Demand*task	3.67***	

Discussion

The current work provides a detailed description of how a submarine control room functions when completing INSO operations. The social, information and task networks demonstrate the complexities involved when completing submarine INSOs (Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015; Loft, Sadler, Braithwaite, & Huf, 2015; Stanton, & Bessell, 2014; Huf, Arulampalam, Masell, Tynan, Brown, Manning, 2004). The current work offers support for previous work examining submarine operations from a sociotechnical perspective (Stanton, 2014). However there are differences in terms of the social, information and task networks, as the operational environment and mission requirements are different (Bateman, 2011).

Demand

The number of emissions and receptions between operators in the high demand INSO condition significantly increased, as did the information elements and the frequency of task completion. This indicates that a strategy undertaken by the command team to adapt to greater demand is increasing the volume of communications, passing more information, more frequently whilst completing a greater number of tasks. If the number of communications and volume of information passed between command teams members continue to increase with demand, this would have a negative impact upon performance (Salas, Cooke, & Rosen, 2008; Stanton, 2011, Salas, Burke, & Samman, 2001; Carletta, Anderson, & McEwan, 2000). The fundamental perceptual capacities of humans mean that only a finite amount of information can be communicated (Baddeley, 2000). Moreover, the communication technologies (e.g. headsets and radio network) and interface designs may place physical limitations on the passage of critical information (e.g. one operator monopolising the network). This supports previous work that stated technological advancements (i.e. improved sensor capabilities) does not necessarily improve command team performance (Dominguez, et al., 2006; Roberts, Stanton & Fay, 2015). Other media to support command team communication and sharing of information need to be explored (Stanton, Connelly, Prichard & van Vugt, 2002).

Social Network Analysis

The operator with the highest number of emissions (apart from command – OOW, OPSO and SOC) was PERI. When completing INSO the waters are typically shallow increasing the potential for collisions with surface vessels (Glosny, 2004; Holt, Noren, Veirs, Emmons, & Veirs, 2009; Duryea, Lindstrom, & Sayegh, 2008). A key requirement of submarine operation is to maximise the safety of surrounding vessels (Jones, Steed, Diedrich, Armbruster, & Jackson, 2011). The optimal way for a submarine to stay safe in shallow, busy, waters is to use visual data from PERI, whilst periscope also supports key INSO mission objectives (Bateman, 2011). It is for such reasons that PERI also has the highest sociometric status of all operators (except command). OPSO has the largest number of emissions and receptions of all operators in the command team. OPSO is responsible for integrating information from numerous instruments (e.g. sonar and visual) to provide OOW with a tactical picture as when operating at shallower depth. It is critical that the periscope is not raised too frequently as a primary objective of submarines is remaining covert (Bateman, 2011). It is for this reason that the centrality and sociometric status of OPSO is high, as they are required to communicate with SOC regarding sonar data when periscope is lowered and with PERI for visual information when periscope is raised.

The sociometric status and centrality of the SOPs and TMAs is relatively similar and much lower than command and PERI. The wash created when periscope is raised reduces sonar usefulness (Glosny, 2004). Therefore the SOPs communicate less as the availability of sonar is intermittent. The TMAs are still required to generate contacts solutions, however the information received from periscope is less ambiguous than passive sonar, facilitating the generation of solutions with less communication (Dominguez, Long, Miller, & Wiggins, 2006; Ogden, Zurk, Jones, & Peterson, 2011; Holt, Noren, Veirs, Emmons, & Veirs, 2009). However, the betweeness of the SOPS and

TMAs is extremely low further indicating how the command team structure results in high communication load being placed on OPSO (Stanton, Rothrock, Harvey & Sorensen, 2015; Espevik, Johnsen, Eid, & Thayer, 2006).

Information Network analysis

The information elements with the highest sociometric status are ‘bearing’ and ‘speed’. When operating at shallower depths the potential for collisions is greatly increased (Duryea, Lindstrom, & Sayegh, 2008; Champagne, Carl, & Hill, 2003). Knowledge of surrounding vessel’s bearing and the speed at which they are traveling assists both safety and navigation inshore to complete mission objectives (Bateman, 2011). Information relating to the ‘range’ and ‘course’ of surrounding vessels also has high sociometric status, particularly during the high demand INSO scenarios. This information is also important for safety (e.g. to be aware that vessels are at a safe distance from the submarine), although ‘speed’ and ‘bearing’ may be more critical for predicting the future behaviour of vessels. This suggests that, during INSO, submarines function in a more reactive fashion, rather than during a RTPD where tasks might be completed procedurally (Stanton, 2014). During INSO, submarines may continually alter a navigational plan to reach a set point safely (e.g. to gather intelligence) through densely populated costal littoral zones (Duryea, Lindstrom, & Sayegh, 2008).

The information element with the greatest betweeness is ‘contact’. When operating inshore, submarines must be aware of surrounding ‘contacts’ (Jones, Steed, Diedrich, Armbruster, & Jackson, 2011). Information such as ‘bearing’, ‘speed’ and ‘course’ all relate to knowledge of ‘contacts’. ‘Periscope’ information has higher centrality and sociometric status than ‘sonar’ offing further support that periscope is the primary instrument used by the command team during INSO. However, the information ‘sonar’ and ‘visual’ have similar centrality and betweeness ratings suggesting that both information types are utilised by the command team but periscope is most predominantly used for ensuring safety and mission objectives. This is a good example of how submarine command teams are required to integrate data from different sensors and with each other and with various technologies in the control room (Dominguez, Long, Miller, & Wiggins, 2006; Huf, Arulampalam, Masell, Tynan, Brown, Manning, 2004).

Task Network Analysis

The task that was completed most frequently was making changes to own submarine parameters, independent of demand. This offers further support for the fact that to operate safely a submarine must manoeuvre more frequently in a reactive manner to avoid surface vessels (Jones, Steed, Diedrich, Armbruster, & Jackson, 2011; Bateman, 2011; Duryea, Lindstrom, & Sayegh, 2008). Due to the potential shallow waters associated with coastal regions, the command team will need to be aware of, and alter depth, more frequently (Glosny, 2004). Detecting and ranging visual contacts are amongst the most frequently completed tasks. Knowing the range of surrounding vessels is critical for safe submarine operations. This information is likely to be more accurate than TMA solutions based upon sonar data, which is why it is the instrument most frequently used (Glosny, 2004; Ogden, Zurk, Jones, & Peterson, 2011; Zarnich, 1999). Task related to sonar data are typically completed with similar frequency to tasks using periscope. This suggests that the command team utilises both visual and sonar data, in a reciprocal manner, to ensure submarine safety and maintain covertness. It is important that periscope is not raised too frequently or for excessively long periods of time (Bateman, 2014; Zarnich, 1999).

Conclusions

Understanding how instruments, sensors and interfaces facilitate the generation of a tactical picture during submarine operations is a challenge due to the complexity of sociotechnical systems (Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015; Huf, Arulampalam, Masell, Tynan, Brown, Manning, 2004; Stanton, & Bessell, 2014). The current work has provided empirical evidence for clear delineations between submarine command team operators in terms of social, information and task network analysis. During INSO information from periscope is critical as this is the sensor that primality facilitates safety and mission objectives. However, to remain operationally covert, visual data must be supported by passive sonar data as the periscope cannot be raised all of the time. In the current submarine control room sonar and periscope are completely separate both in terms of proximity and operation. Only OOW and OPSO have awareness of both information streams.

Implications

Future submarine control rooms may benefit from automating the collation of data from different sensors and instruments (e.g. visual vs. passive sonar), to supplement operator interpretation. An example of this may be that the bearing at which sonar detections are encountered could automatically be overlaid on a search periscope interface in the form of a 'mash-display'. This also highlights an overreliance on OPSO and in particular the communication between OPSO and PERI and OPSO and SOC. OPSO is reaching maximum capacity in terms of the information that can reasonably be handled, resulting in task shedding during the higher demand INSO scenario (e.g. checking cuts). Future research should examine whether a change in command structure and control room layout may facilitate direct communication between operators who are routinely sharing information via OPSO (e.g. SOPs and TMAs). The current work provides a greater understanding of the functionality of current submarine control rooms during an INSO, whilst also providing a baseline from which to compare future ways of working.

Key points:

- This study examined, from a sociotechnical perspective, submarine command team performance during the completion of high and low demand Inshore Operation (INSO) scenario.

- Results indicate that the Operations Officer (OPSO) had statistically significantly (p<.05) more emissions and receptions than any operator in both the high and demand scenarios. This operator was revealed as a potential bottleneck in the network.

- Statistically significant differences (p<.05) were observed in terms of the volume of information exchanged and task completed between higher and lower demand INSO scenarios. Although the type of information and task completed remained relatively consistent between higher and lower demand scenarios.

- Future submarine control rooms may benefit from ‘mash-displays’ to facilitate operator integration of similar information from different sensors and instruments. The current work also provides insight into how the layout and team structure of future submarine control rooms may be improved to maximise passage of information between operators who are highly reliant on each other for task completion.

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