Go Deeper, Go Deeper: Understanding submarine command and control during the completion of dived tracking operations

Aaron P. J. Roberts\*, Neville A. Stanton a and & Daniel Fay b

University of Southampton,

Building 176, Boldrewood Innovation Campus,

Burgess Road,

Southampton,

UK

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\*Corresponding author Aaron Roberts is with the University of Southampton, Southampton,

UK (e-mail: apr1c13@soton.ac.uk,).

a Neville Stanton is with the University of Southampton, Southampton, UK (e-mail: n.stanton@soton.ac.uk).

b Daniel Fay is with the University of Southampton, Southampton, UK (e-mail:

d.t.fay@soton.ac.uk).

**Abstract**

This is a world’s first-of-a-kind study providing empirical evidence for understanding submarine control room performance when completing higher and lower demand Dived Tracking (DT) scenarios. A submarine control room simulator was built, using a non-commercial version of Dangerous Waters as the simulation engine. The creation of networked workstations allowed a team of nine operators to perform tasks completed by submarine command teams during DT. The Event Analysis of Systemic Teamwork (EAST) method was used to model the social, task and information networks and describe command team performance. Ten teams were recruited for the study, affording statistical comparisons of how command team roles and level of demand affected performance. Results indicate that command teams can covertly DT a contact differently depending on demand (e.g. volume of contacts). In low demand it was possible to use periscope more often than in high demand, in a ‘duck-and-run’ fashion. Therefore, the type of information and frequency of particular task completion, was significantly different between the higher and lower demand conditions. This resulted in different operators in the command team experiencing greater demand depending on how the DT mission objective was completed. Potential bottlenecks in the command team were identified and implications are discussed alongside suggestions for future work.

**Key words:** Submarine, Team Work, Networks

**Introduction**

**Submarine Command and Control: Dived tracking**

A dive tracking (DT) operation requires a submarine command team to covertly track a ‘priority’ contact whilst simultaneously ensuring overall submarine safety via adequate track management of the entire tactical picture (Loft, Morrell, Ponton, Braithwaite, Bowden, & Huf, 2016; Bateman, 2011; Loft, Morrell, & Huf, 2013; Huf, & French, 2004). Submarines are equipped with a range of sensors and instruments which generate a large amount of data that operators in the control room must integrate to facilitate the generation of a tactical picture (Dominguez, Long, Miller, & Wiggins, 2006; Huf, Arulampalam, Masell, Tynan, Brown, Manning, 2004; Shattuck, & Miller, 2006; Stanton, 2014; Stanton & Bessel, 2014). A DT operation typically requires a submarine to operate below periscope depth (63 meters) to ensure covertness, reducing the number of instruments available (e.g. periscope) to the command team forcing a reliance on passive sonar. The accuracy of passive sonar for developing the tactical picture can be greatly affected by oceanographic conditions (e.g. water temperature) and background noise (e.g. multiple vessels) (Zarnich, 1999; Ogden, Zurk, Jones, & Peterson, 2011; Kirschenbaum, 2001). This requires the submarine command team to build a tactical picture from large volumes of ambiguous information, operating with great uncertainty (Kirschenbaum, 2001). Even DTof surface vessels from deep is a challenge, particularly when military surface vessels use technology to reduce chances of detection (Koubeissi, Pomie, & Rochefort, 2013; Xuan, & Li, 2006).

The development of new technologies and new methods for fusing data when tracking priority contacts using external equipment (e.g. sonobuoys) could extend capability (Wang, Chen, Blasch, Lynch, & Pham, 2011). However, the placement of such technologies is not always possible due to logistical, operational or legal restrictions. Therefore the ability of submarines to self-sufficiently covertly track other vessels remains a critical operation (Bateman, 2011). This is particularly important as a shift in the tactical deployment of submarines by some nations is likely to lead to an increase in the requirement to dive track other submarines (Li, 2009; Bateman, 2011). Research has sought to develop new software algorithms and architectures to make the tracking of contacts by submarines more efficient and accurate (Shar, & Li, 2000; Wang et al., 2011; Lim, 2012). However, such work does not examine how the technology might be used within the submarine control room and the impact it may have on the sociotechnical system as a whole (Walker, Stanton, Salmon & Jenkins, 2009). Therefore, a primary aim of the current work is to evaluate submarine control rooms from a sociotechnical perspective, providing insight and a baseline comparator, to understand how new data and/or operators, might be optimally integrated into the system.

**Sociotechnical systems – control rooms**

A sociotechnical system is defined as the interaction of human operators and technology, to pursue broader goal-directed behaviours creating the conditions for successful overall performance (Walker, Stanton, Salmon, & Jenkins, 2008; Walker et al., 2009). In sociotechnical systems, effective sharing of information is critical as cognitive processes and situation awareness (SA) are not held by one agent or individual but rather are distributed across the control room (Stanton, 2014; Stanton, 2016; Read, Salmon, Lenné, & Stanton, 2015). The capacity to DT a vessel relies on the commanding officer having an accurate tactical picture and reliable information concerning the priority contact’s behaviour. The commanding officer is ultimately responsible for the safety of the submarine but decision effectiveness relies on the effective integration of large volumes of information from disparate sources, both technological and human (Dominguez et al., 2013). The sociotechnical systems perspective therefore offers a valid theoretical grounding for understanding submarine control room functionality (Stanton, 2014). Understanding the distribution and sharing of information within command teams can help to inform the optimal design of control rooms and technologies (e.g. interfaces) within them across many domains (Stanton, 2014; Stanton, 2011, Salas, Burke, & Samman, 2001; Lee, & Kantowitz, 2005). The manner in which a team is configured and how technology supports communication can also influence their effectiveness (Stanton, Rothrock, Harvey & Sorensen, 2015; Espevik, Johnsen, Eid, & Thayer, 2006).

The ability of submarine control room teams to track contacts has been investigated previously (Loft, et al., 2016; Loft et al., 2013; Huf, & French, 2004). Such work has provided valuable insight into the SA of track management. However, this work was individualistic and did not approach the task from a sociotechnical systems perspective. A returning to periscope depth scenario has been investigated from a sociotechnical perspective, providing insights into the functions of a submarine command team (Stanton, 2014; Stanton, & Bessell, 2014). However, it is likely that differences in control room functionality will be evident in different operational contexts such as a DT or Inshore Operation compared to a return to periscope depth (Stanton, 2014; Duryea, Lindstrom, & Sayegh, 2008; Bateman, 2011; Stone, Caird-Daley, & Bessell, 2009). The ability of a submarine command team to track contacts has been approached from a sociotechnical perspective (Hunter, Hazen, & Randall, 2014). Such work outlined an experimental design approach, but the empirical contribution of the work was limited to 2 teams. A great challenge in this pursuit is the recruitment of large numbers of teams to provide evidence with good statistical power that is generalizable. This issue has been highlighted in studies comparing a large individualistic student cohort to a smaller team-based expert cohort of submariners, where great differences in time taken to establish SA and tactical picture quality were observed (Loft, et al., 2016). Nevertheless, the recruitment of novice participants with effective training procedures and relative task fidelity has been demonstrated to be a good approach for balancing ecological validity and statistical reliability in the military domain (Walker, Stanton, Salmon, Jenkins, Rafferty, & Ladva, 2010). Therefore, the recruitment of larger numbers of novice teams provides an opportunity to provide empirically robust insights into submarine command team functionality from a sociotechnical and macrocognitive perspective (Keyton, Beck, & Asbury, 2010; Wallace & Hinsz, 2010). This can provide formalisation of constructs and clear defining measurable parameters to inform evidence based design of future control rooms (Thomson, Lebiere, Anderson & Staszewski, 2015).

**Optimising control rooms of the future**

As technology continues to rapidly advance, sociotechnical systems are primed for revolutionary changes in ways of working to increase capability (Roco & Bainbridge 2003; Showalter, 2005). This drive is not only evident for the submarine domain (Stanton, 2014), but also for surface vessels (Lützhöft, & Dekker, 2002; Negahdaripour, & Firoozfam, 2006), aviation (Rudisill, 2000; Bruce, Rice, & Hepp, 1998; Stanton, Harris, & Starr, 2016) and gas/electric/nuclear power plants (Santos, Teixeira, Ferraz, & Carvalho, 2008; Stanton, Salmon, Jenkins & Walker, 2009; Stanton, Salmon, Jenkins & Walker, 2010). In many of these domains control rooms are required, their commonality being a reliance 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 et al., 2001; Carletta, Anderson, & McEwan, 2000).

A critical challenge when optimising the design and operation of control rooms is that they are complex by nature and as a result knowledge is not easily attained and shared by operators, manufacturers and researchers alike. This is compounded by the fact that control rooms in many domains manage hazardous systems and are often subject to heightened security and regulation (Roberts, Stanton & Fay, 2015). Understanding the strengths and weaknesses of control rooms from a sociotechnical systems perspective across different domains, operations and with different levels of demand will facilitate this. It is important to understand how a submarine DT other vessels in conditions of both high and low demand (e.g. varied number of contacts), to inform the design of adaptive, flexible control rooms. Primarily because submarines of the future will encounter greater variability in demand due to changing numbers of vessels in the water, both surface and submerged, coupled with variations in the primary locations that submarine operations are completed (Bateman, 2011; Duryea, Lindstrom, & Sayegh, 2008).

The current work sought to examine DT operations from a sociotechnical systems perspective. The examination of multiple command teams facilitated empirical examination of command team performance. We also investigated the effect of different operational demand on command team strategies by using both higher and lower demand DT scenarios.

**Method**

**Participants**

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 Ministry of Defence supported companies. The 10 teams of 8 individuals (80 participants in total) were recruited opportunistically using posters and presentations at military Human Factors conferences. One team were currently operational submariners from the British Royal Navy. This team was used as a subject matter expert ‘gold-standard’ to assess the fidelity of the simulator and tasks. The metrics derived from the expert team revealed similar directions to the novice teams (e.g. did not violate assumptions of statistical analysis) and so it was decided to include this team in the analysis process to enhance statistical power. Participation in the study was voluntary.

**Equipment - The Submarine control room simulator**

A submarine simulator based upon a currently operational submarine was designed and built by the research team (see Roberts et al., 2014 for full description of simulator). The simulator was comprised of 9 network workstations (see figure 1) that were running Dangerous Waters (DW) as the simulation engine. DW is a naval warfare simulation developed by Sonalysts which features many player-controllable units from a submarine control room. The workstations are networked so operators can function as a command team in support of global mission objectives. Subject matter experts informed the choosing of stations to include in the simulator to be representative of an operational submarine control room. The stations chosen were a Periscope station (PERI), a Ship Control station (SHC), two Sonar Operator stations (SOP), two Target Motion Analysis stations (TMA), a Sonar Controller station (SOC), an Operations Officer station (OPSO) and an Officer of the Watch station (OOW). An array of web camera, video camera, ambient microphone and headset recording software was used to record all communications between operators in the simulator. Subject matter experts also facilitated the design of high and low demand DT scenarios, programmed in DW (see table 1). The movement of contacts was predetermined to be consistent, each scenario lasted approximately 45 minutes.



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 9 mixed design (social networks), a 2 x 14 repeated measures design (information networks) and a 2 x 12 repeated measures design (task networks). The independent variables were scenario demand (within subjects), operator role (between subjects - social network), information type (within subjects – information network) and task type (within subjects – task network). Scenario demand was manipulated by the number of contacts detectable in the scenario, contact behaviour (e.g. speed and course changes vs. steady) and area of operation (see table 1). The design of scenarios was informed by subject matter experts to be representative of real high and low demand dived tracking operations. The dependent variables were static adjacency matrices (social, information and task) derived from the communications that took place between operators within the command team.

Table 1. *Description of scenarios designed*

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Demand | No. Contacts | Mission |
| Dived Tracking(DT) | Low | 3 – Fishing1 – Sailboat1 - Nimitz | Starting at Periscope Depth (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 - Merchant1 - Nimitz | Locate and track priority contact (Nimitz warship) in nearby waters, after near collision forces emergency go deep procedure |

**Procedure**

Participants attended the simulator facility for two full days from 8am to 5pm. On the first day (training) participants signed a consent form, a simulator induction was performed and operator roles were randomly assigned. Participants then spent the morning watching the first 3 video tutorials as a group, each was approximately 45 minutes in length (see table 2 for a description of tutorials). In between tutorials the experimenters encouraged questions regarding tasks and how the command team should interact, a 15 minute break was provided between each tutorial. Participants then completed an ‘anagram game’ which brought together all aspects of the morning training session. Participants were then given a 45 minute lunch break.

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, to listen to a contact, how to designate a track 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 DT scenario completion | Participants completed shortened versions of the 2 scenarios (DT) 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.  |

In the afternoon participants received tutorials specific to the workstation they had been assigned. Participants were seated at their relevant workstation and had the tutorial running on a top screen and a training version of their workstation interface on the bottom screen. This allowed participants to pause aspects of the tutorial and practice task completion interactively. The final part of training was dedicated to completing practice DT scenarios as a command team, completing a minimum of 2 shortened training scenarios (1 hour in total). By the end of the training day each member of the command team was required to demonstrate the capacity to perform all tasks required to be completed as part of their role (e.g. sonar operator – designate contacts, generate speed estimates) as outlined by subject matter experts when developing the training package. If during the final training scenario a command team would not have been able to adequately develop a tactical picture and track an evading contact they would have been excluded from the testing day, however all teams were able to demonstrate this capacity in line with the assessment criteria developed with subject matter experts.

On the second day (testing) participants attended the simulator and initially completed a refresher training scenario as a command team. Experimenters watched the performance of operators, checking that operators were completing tasks at individual workstations effectively. Participants then completed the high and low demand DT testing scenarios. Participants were told that the first scenario would begin – all recording devices were started and a verbal time stamp was read aloud for synchronization purposes. 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. Once 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.

**Analysis of data**

A new shortened version of Event Analysis for Systemic Teamwork (EAST: Stanton, Baber & Harris, 2008) was used to analyse the data. EAST examines complex sociotechnical systems using a network approach. The raw data from video cameras and microphones was used to generate three types of networks; social, information and task. This method has been used in many domains including aviation (Stewart, Stanton, Harris, Baber, Salmon, Mock, & Kay, 2008; Stanton & Harvey, 2016), naval warfare (Stanton, Salmon, Walker, & Jenkins, 2009), emergency services (Houghton, Baber, McMaster, Stanton, Salmon, Stewart, & Walker, 2006), and most pertinently to model submarine command and control (Stanton, 2014). Social networks examine the communications made between ‘agents’ in the system; information networks detail the type of information that is passed between agents in the system and task networks describe the tasks that are completed by agents in the system and the dependencies between tasks. These networks were processed using AGNA software (version 2.1.1 – a software program for computing the Social Network metrics). The audio recordings were transcribed and a frequency count of communications between agents was compiled in adjacency matrices for each team. The nodes in the information networks were determined using Leximancer software (version 2.1 – a software program for identifying concepts in text documents), the top 14 information elements (according to frequency count) were included in the statistical analysis of the information nodes. The task nodes were derived by watching the ambient videos, screen recordings and listening to audio to ascertain what particular tasks were performed. This was completed by subject matter experts before frequency counts of all tasks were completed.

A number of metrics can be acquired via AGNA to facilitate the quantitative assessment of the networks including global network metrics (e.g. density, diameter and cohesion – see table 3) and individual nodal metrics (e.g. sociometric status and centrality of each node – see table 3). A description of network typology is provided in previous work (Stanton, 2014). The data was assessed to check it met the requirements (e.g. distribution and homogeneity) for parametric analysis to be conducted. When examining network nodes the effects of scenario demand and operator role (social network metrics) were analysed by completion of a 2 x 8 mixed analyses of variances (ANOVA). A 2 x 14 repeated measures ANOVA was conducted to examine the effects of scenario demand and information type (information network metrics). To examine the effects of demand on entire network composition paired t-tests were conducted to examine both social and information networks. The nodes and composition of the task networks were not examined as the composition of the task networks was the same during the high and low demand scenarios across all teams. However, a 2 x 12 repeated measures ANOVA was conducted to examine the impact of demand on task completion frequency (task network metrics). All significant main effects were examined by conducting post hoc pairwise comparisons. To account for multiple post hoc comparisons the Bonferroni correction method was used (α = 0.05/number of comparisons). All statistical analyses were conducted using IBM SPSS v21.

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 from one side of the network to the other |

|  |  |
| --- | --- |
| 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 |
| Closeness | Inverse of the sum of the shortest distances between each individual and every other person in the network. |
| Farness | Sum of each node to all other nodes in the network by the shortest path |
| Betweenness | Number of times a node lies on the shortest path between other nodes |
| Eccentricity | The number of relations in the shortest possible distance from node actor to another |

**Results**

The results sections will be split into sections detailing visual inspection of network diagrams, examination of the whole network composition and examination of the individual nodes in each network. The social networks are examined first, providing examination of how information in the control room flowed between operators. Secondly, the information networks are examined which provides evaluation of what information is being passed around the control room. Finally, the task networks are examined along with the frequency on task completion.

**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 appeared to increase during the high demand DT scenario.



**Figure 2.** *Social network diagrams for low and high demand DT scenarios. The lines indicate the average number of emissions and receptions between operators in the command team (weighted lines reveal stronger connections). The numbers indicate the mean number of emissions and receptions between each operator node used to inform line thickness.*

**Whole Network Metrics**

The total network emissions and receptions was statistically significantly higher in the high demand DT condition than the low demand condition (*t*9 = 4.50, p < .01, *d* = 1.47, see table 4). No other statistically significant effects were observed, indicating the structure of the network remained relatively consistent in both higher and lower demand conditions.

Table 4*. Social network Metrics for entire network DT*

|  |  |  |
| --- | --- | --- |
|  | DT | Effect of Demand (t Value) |
|  | Low | High |  |
| Nodes | 9 | 9 | NA |
| Edges | 32.00 ± 3.37 | 32.66 ± 2.11 | 0.50 |
| Density | 0.44 ± 0.05 | 0.45 ± 0.03 | 0.60 |
| Cohesion | 0.32 ± 0.02 | 0.34 ± 0.05 | 0.50 |
| Diameter | 3 ± 0.00 | 3 ± 0.00 | 0.00 |
| Total Interactions | 634.90 ± 142.64 | 787.78 ± 106.92 | 4.50\*\*\* |

**Nodal Metrics**

**Emissions**

The total emissions of each node were significantly affected by scenario demand (*F*1, 81 = 52.45, *p* < .01, ήp2 = .40) and operator role (*F*8, 81 = 71.36, *p* < .01, ήp2 = .88). The interaction of scenario demand and role also statistically significantly affected total node emissions (*F*8, 81 = 6.08, *p* < .01, ήp2 = .38). When examining the effect of scenario demand, post hoc analysis revealed emissions were statistically significantly higher (*p*<.05) in the high demand DT condition than the low demand condition for OOW, OPSO, SOC, SOP1, SOP2, TMA1 and TMA2 (see table 5 and figure 2). When examining the effect of operator role, post hoc analysis revealed OPSO and SOC had a statistically significantly (*p*<.05) greater number of emissions than all other operators. OOW had statistically significantly (p<.05) higher emissions than all operators (except OPSO and SOC).

Table 5. *Social network metrics for individual nodes DT low and high demand scenario*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | Emission | Reception | Sociometric  | Centrality | Betweenness |
|  | N | Low | High | Low | High | Low | High | Low | High | Low | High |
| OOW | 10 | 94.4 ± 14.65 | 114.89 ± 18.52 | 88.5 ± 19.45 | 108.22 ± 22.77 | 22.86 ± 3.73 | 27.89 ± 4.85 | 5.87 ± 0.38 | 6.21 ± 0.25 | 14.17 ± 3.07 | 19.35 ± 4.97 |
| OPSO | 10 | 166.5 ± 31.16 | 199.11 ± 20.55 | 158.5 ± 29.38 | 203 ± 18.68 | 40.63 ± 7.18 | 50.27 ± 4.8 | 5.77 ± 0.24 | 5.64 ± 0.16 | 18.53 ± 4.75 | 17.69 ± 2.07 |
| SOC | 10 | 131.7 ± 52.72 | 177.56 ± 35.88 | 126.1 ± 40.34 | 183.89 ± 36.86 | 32.23 ± 11.56 | 45.18 ± 8.52 | 5.65 ± 0.15 | 5.28 ± 0.14 | 15.72 ± 2.57 | 8.83 ± 3.18 |
| SOP1 | 10 | 45.2 ± 27.66 | 62.67 ± 21.09 | 52.8 ± 28.68 | 65.44 ± 32.58 | 12.25 ± 6.96 | 16.02 ± 6.64 | 3.88 ± 0.23 | 3.99 ± 0.33 | 0.07 ± 0.21 | 0.61 ± 0.87 |
| SOP2 | 10 | 38.9 ± 23.57 | 51.11 ± 20.91 | 48.7 ± 26.75 | 53.78 ± 23.74 | 10.95 ± 6.22 | 13.11 ± 5.27 | 4.18 ± 0.85 | 4.09 ± 0.34 | 0 ± 0 | 0.63 ± 0.94 |
| TMA1 | 10 | 46.1 ± 15.39 | 60.89 ± 14.43 | 58.3 ± 16.79 | 63.56 ± 18.7 | 13.05 ± 3.81 | 15.56 ± 3.94 | 3.96 ± 0.32 | 3.94 ± 0.09 | 0.2 ± 0.63 | 0 ± 0 |
| TMA2 | 10 | 43.3 ± 13.45 | 58.56 ± 13.2 | 52.2 ± 16.09 | 63.11 ± 11.81 | 11.94 ± 3.56 | 15.21 ± 3.07 | 3.87 ± 0.13 | 3.95 ± 0.09 | 0 ± 0 | 0.13 ± 0.37 |
| PERI | 10 | 48.8 ± 16.92 | 32.56 ± 16.67 | 32.9 ± 15.55 | 21.44 ± 15.78 | 10.22 ± 3.69 | 6.75 ± 3.67 | 5.26 ± 0.26 | 5 ± 0.33 | 4.82 ± 2.31 | 2.76 ± 1.68 |
| SHC | 10 | 23 ± 6.62 | 30.44 ± 16.18 | 19.9 ± 5.82 | 25.33 ± 6.73 | 5.36 ± 1.33 | 6.98 ± 2.57 | 3.7 ± 0.21 | 3.79 ± 0.19 | 0 ± 0 | 0 ± 0 |
| Effect of Demand(f Value) |  | 52.45\*\*\* | 45.74\*\*\* | 54.75\*\*\* | .50 | 1.71 |
| Effect of Role(f Value) |  | 71.36\*\*\* | 73.91\*\*\* | 78.40\*\*\* | 139.07\*\*\* | 205.60\*\*\* |
| Demand\*Role(f Value) |  | 6.08\*\*\* | 8.50\*\*\* | 7.91\*\*\* | 3.12\*\*\* | 12.32\*\*\* |

**Receptions**

The total receptions of each node were significantly affected by scenario demand (*F*1, 81 = 45.74, *p* < .01, ήp2 = .36) and operator role (*F*8, 81 = 73.91, *p* < .01, ήp2 = .88). The interaction of scenario demand and role also statistically significantly affected total node receptions (*F*8, 81 = 8.50, *p* < .01, ήp2 = .46). When examining the effect of scenario demand, post hoc analysis revealed receptions were statistically significantly higher (*p*<.05) in the high demand inshore operation condition than the low demand condition for OOW, OPSO and SOC (see table 5 and figure 2). When examining the effect of operator role, post hoc analysis revealed OPSO and SOC had a statistically significantly (*p*<.05) greater number of receptions than all other operators. OOW had statistically significantly (p<.05) higher reception than all operators (except OPSO and SOC).

**Sociometric Status**

The sociometric status of each node was significantly affected by scenario demand (*F*1, 81 = 54.75, *p* < .01, ήp2 = .40) and operator role (*F*8, 81 = 78.40, *p* < .01, ήp2 = .89). The interaction of scenario demand and role also statistically significantly affected total node receptions (*F*8, 81 = 7.91, *p* < .01, ήp2 = .44). When examining the effect of scenario demand, post hoc analysis revealed that sociometric status was statistically significantly higher (*p*<.05) in the high demand DT condition than the low demand condition for OOW, OPSO and SOC. The sociometric status of PERI was statistically significantly (*p*<.05) lower in the high demand DT condition. When examining the effect of operator role, post hoc analysis revealed OPSO and SOC had statistically significantly higher sociometric status than all operators (*p*<.05). OOW had statistically significantly (p<.05) higher sociometric status than all operators (except OPSO and SOC).

**Centrality**

The centrality of each node was not statistically significantly affected by scenario demand (*F*1, 81 = 0.5, *p* > .05) but was statistically significantly affected by operator role (*F*8, 81 = 139.07, *p* < .01, ήp2 = .93) and the interaction between scenario demand and role (*F*1, 81 = 3.12, *p* < .05, ήp2 = .24). When examining the effect of operator role, post hoc analysis revealed OOW had statistically significantly (p<.05) higher centrality than all operators. OPSO had statistically significantly (p<.05) higher centrality than all operators (except OOW). SOC and PERI had statistically significantly (p<.05) higher centrality than all other operators. SOP2 had statistically significantly (p<.05) higher centrality than SHC. When examining the interaction of scenario and demand, post hoc analysis revealed similar effects to those observed when examining the effect of role. Notable exceptions to this was OOW, who had statistically significantly (p<.05) higher centrality than OPSO and SOC in the DT high demand condition, but not during the low demand condition. OPSO had statistically significantly (p<.05) higher demand than PERI in the high demand DT condition but not in the low demand condition.

**Betweenness**

The betweenness of each node was not statistically significantly affected by scenario demand (*F*1, 81 = 1.71, *p* > .05) but was significantly affected by operator role (*F*8, 81 = 43.69, *p* < .01, ήp2 = .81) and the interaction between scenario demand and role (*F*1, 81 = 12.32, *p* < .01, ήp2 = .95). When examining the effect of operator role, post hoc analysis revealed the betweenness of OPSO and OOW was statistically significantly higher (*p*<.05) than all operators. The betweenness of SOC was statistically significantly higher than all operators (except OPSO and OOW). PERI had statistically significantly (p<.05) higher betweenness than SOP1, SOP2, TMA1, TMA2 and SHC.

**Information Network Analysis**

The structure of the information networks was relatively consistent in both high and low demand DT scenarios with ‘contact’, ‘bearing’ and ‘speed’ the most connected information elements (see figure 3). The volume of emissions from most information elements appeared to increase in the high demand DT scenario although differences in relationships can be observed.





Figure 3. *Information network diagrams for low and high demand DT scenarios. The lines indicate the primary connections between information nodes. The numbers indicate the total number of times each information node was directly connected (according to Leximancer software) across all 10 teams.*

**Whole Network Metrics**

The total number of edges was statistically significantly (*t*9 = 2.20, *p* < .05, *d* = 0.46) higher in the high demand condition. The total number of emissions (*t*9 = 3.54, *p* < .05, *d* = 0.90) was statistically significantly higher in the high demand condition (see table 6). This indicates that the volume of information passed between operators and connectivity between information was greater in the high demand DT scenario.

Table 6*. Information network Metrics for entire network DT*

|  |  |  |
| --- | --- | --- |
|  | DT | Effect of Demand (t Value) |
|  | Low | High |  |
| Nodes | 42.80 ± 4.10 | 47.78 ± 7.86 | 1.75 |
| Edges | 615.60 ± 253.32 | 732.33.40 ± 257.72 | 2.20\* |
| Density | 0.54 ± 0.21 | 0.60 ± 0.27 | 0.89 |
| Cohesion | 0.38 ± 0.12 | 0.38 ± 0.73 | 0.10 |
| Diameter | 2.90 ± 0.73 | 2.89 ± 0.73 | 0.51 |
| Total Emissions | 2409.20 ± 948.09 | 3693.67 ± 1471.06 | 3.54\*\* |

**Nodal Metrics**

**Emissions**

The total emissions of each node were statistically significantly affected by scenario demand (*F*1, 126 = 56.33, *p* < .01, ήp2 = .31) and concept type (*F*13, 126 = 12.00, *p* < .01, ήp2 = .55). A statistically significant interaction (*F*13, 126 = 4.25, *p* < .01, ήp2 = .31) between scenario demand and concept type was also observed. Post hoc analysis revealed emissions were statistically significantly higher (*p*<.05) in the high demand DT condition than the low demand condition. Post hoc analysis revealed bearing emissions were statistically significantly higher (*p*<.05) than all information pieces except course, merge, solution, speed and range. Course emissions were statistically significantly (*p*<.05) higher than look, periscope, priority, cuts, depth and visual. Emissions for merge were statistically significantly (*p*<.05) higher than for look, periscope, priority, cuts, depth and visual. Solution emissions were statistically significantly (*p*<.05) higher than look, periscope, priority, cuts, depth and visual. Speed emissions were statistically significantly higher (*p*<.05) than all information pieces except bearing and course. Range emissions were statistically significantly higher (*p*<.05) than for priority, cuts, depth and visual (see table 7 and figure 3).

Table 7. *Information network metrics for individual nodes DT low and high demand scenario*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Emission | Reception | Sociometric  | Centrality | Betweenness |
|  | Low | High | Low | High | Low | High | Low | High | Low | High |
| Bearing | 189.59 ± 105.06 | 343.21 ± 117.27 | 189.59 ± 105.06 | 343.21 ± 117.27 | 9.19 ± 4.76 | 15.54 ± 6.13 | 28.04 ± 4.25 | 30.78 ± 5.20 | 139.63 ± 75.67 | 137.94 ± 80.24 |
| Contact | 116.48 ± 48.74 | 115.37 ± 72.81 | 116.48 ± 48.74 | 115.37 ± 72.81 | 5.60 ± 2.37 | 5.35 ± 3.58 | 28.38 ± 5.41 | 29.08 ± 5.93 | 160.03 ± 172.77 | 137.03 ± 136.65 |
| Course | 141.35 ± 49.15 | 290.55 ± 95.69 | 141.35 ± 49.15 | 290.55 ± 95.69 | 7.05 ± 2.86 | 13.07 ± 4.31 | 24.14 ± 3.70 | 28.03 ± 5.50 | 44.85 ± 32.64 | 62.85 ± 43.27 |
| Look | 59.30 ± 33.31 | 73.84 ± 39.70 | 59.30 ± 33.31 | 73.84 ± 39.70 | 2.91 ± 1.73 | 3.32 ± 1.72 | 23.66 ± 3.83 | 26.34 ± 6.44 | 43.81 ± 38.78 | 66.01 ± 106.54 |
| Merge | 143.10 ± 141.17 | 234.25 ± 254.42 | 143.10 ± 141.17 | 234.25 ± 254.42 | 7.61 ± 8.48 | 10.93 ± 12.24 | 24.85 ± 2.39 | 28.32 ± 6.02 | 87.97 ± 72.86 | 91.03 ± 99.25 |
| Periscope | 68.74 ± 34.45 | 65.47 ± 46.80 | 68.74 ± 34.45 | 65.47 ± 46.80 | 3.33 ± 1.75 | 3.09 ± 2.24 | 24.19 ± 4.30 | 25.27 ± 3.59 | 54.63 ± 51.91 | 62.93 ± 37.64 |
| Priority | 53.67 ± 41.76 | 68.54 ± 64.57 | 53.67 ± 41.76 | 68.54 ± 64.57 | 2.60 ± 1.95 | 3.27 ± 3.15 | 22.71 ± 4.47 | 24.78 ± 5.38 | 33.06 ± 39.77 | 45.54 ± 49.76 |
| Solution | 129.40 ± 78.59 | 250.00 ± 136.43 | 129.40 ± 78.59 | 250.00 ± 136.43 | 6.44 ± 4.36 | 11.23 ± 6.50 | 25.09 ± 3.21 | 28.63 ± 5.07 | 51.47 ± 38.59 | 76.58 ± 54.34 |
| Sonar | 84.10 ± 113.53 | 133.91 ± 124.88 | 84.10 ± 113.53 | 133.91 ± 124.88 | 4.14 ± 5.98 | 6.12 ± 5.34 | 24.23 ± 3.86 | 27.15 ± 5.24 | 49.18 ± 45.29 | 62.42 ± 56.96 |
| Speed | 224.47 ± 103.97 | 408.89 ± 176.71 | 224.47 ± 103.97 | 408.89 ± 176.71 | 11.33 ± 6.39 | 18.52 ± 8.55 | 27.36 ± 3.29 | 30.09 ± 6.13 | 134.60 ± 101.24 | 117.47 ± 96.45 |
| Cuts | 27.21 ± 28.02 | 32.14 ± 33.09 | 27.21 ± 28.02 | 32.14 ± 33.09 | 1.32 ± 1.37 | 1.40 ± 1.55 | 19.69 ± 3.65 | 23.20 ± 4.69 | 5.89 ± 7.54 | 14.58 ± 15.41 |
| Depth | 36.37 ± 31.16 | 61.77 ± 68.23 | 36.37 ± 31.16 | 61.77 ± 68.23 | 1.77 ± 1.58 | 2.55 ± 2.62 | 21.90 ± 3.76 | 24.56 ± 6.73 | 23.30 ± 26.55 | 35.08 ± 57.55 |
| Range | 125.26 ± 41.68 | 231.27 ± 125.49 | 125.26 ± 41.68 | 231.27 ± 125.49 | 6.17 ± 2.44 | 10.12 ± 4.60 | 23.93 ± 2.87 | 27.11 ± 5.21 | 26.14 ± 20.44 | 38.96 ± 23.42 |
| Visual | 48.45 ± 27.11 | 49.65 ± 52.05 | 48.45 ± 27.11 | 49.65 ± 52.05 | 2.31 ± 1.35 | 2.20 ± 2.31 | 22.98 ± 2.83 | 24.67 ± 4.90 | 16.29 ± 20.75 | 30.77 ± 33.75 |
| Effect of Demand(f Value) | 56.33\*\*\* | 56.33\*\*\* | 32.19\*\*\* | 19.04\*\*\* | 1.84 |
| Effect of Concept(f Value) | 12.00\*\*\* | 12.00\*\*\* | 11.18\*\*\* | 5.49\*\*\* | 5.14\*\*\* |
| Demand\*Concept(f Value) | 4.25\*\*\* | 4.25\*\*\* | 2.72\*\*\* | .18 | .70 |

**Receptions**

The total receptions of each node were statistically significantly affected by scenario demand (*F*1, 126 = 56.33, *p* < .01, ήp2 = .30) and concept type (*F*13, 126 = 12.00, *p* < .01, ήp2 = .55). A statistically significant interaction (*F*13, 126 = 4.25, *p* < .01, ήp2 = .31) between scenario demand and concept type was also observed. Post hoc analysis revealed receptions were statistically significantly higher (*p*<.05) in the high demand DT condition than the low demand condition. Post hoc analysis revealed bearing receptions were statistically significantly higher (*p*<.05) than all information pieces except course, merge, solution, speed and range. Course receptions were statistically significantly (*p*<.05) higher than look, periscope, priority cuts, depth and visual. Receptions for merge were statistically significantly (*p*<.05) higher than for look, periscope, priority, cuts, depth and visual. Solution receptions were statistically significantly (*p*<.05) higher than look, periscope, priority, cuts depth and visual. Speed receptions were statistically significantly higher (*p*<.05) than all information pieces except bearing and course (see table 7 and figure 3).

**Sociometric status**

The sociometric status of each node was statistically significantly affected by scenario demand (*F*1, 126 = 32.19, *p* < .01, ήp2 = .20) and concept type (*F*13, 126 = 11.18, *p* < .01, ήp2 = .54). A statistically significant interaction (*F*13, 126 = 2.72, *p* < .01, ήp2 = .22) between scenario demand and concept type was also observed. Post hoc analysis revealed sociometric status was statistically significantly higher (*p*<.05) in the high demand DT condition than the low demand condition. Post hoc analysis revealed the sociometric status of bearing was statistically significantly (*p*<.05) higher than all information pieces except course, merge, solution, speed and range. The sociometric status of course was statistically significantly higher (*p*<.05) than look, periscope, priority, cuts, depth, range and visual. Merge had statistically significantly (*p*<.05) higher sociometric status than look, periscope, priority, cuts depth and visual. Solution had statistically significantly higher (*p*<.05) sociometric status than look, periscope, priority, cuts, depth and visual. Speed had statistically significantly (*p*<.05) higher sociometric status than all information pieces except bearing and course.

**Centrality**

The centrality of each node was statistically significantly affected by scenario demand (*F*1, 126 = 19.04, *p* < .01, ήp2 = .13) and concept type (*F*13, 126 = 5.49, *p* < .01, ήp2 = .36). Post hoc analysis revealed centrality was statistically significantly higher (*p*<.05) in the high demand DT condition than the low demand condition. Post hoc analysis revealed the centrality of bearing was statistically significantly (*p*<.05) higher than priority, cuts, depth and visual. Contact and speed had statistically significantly (*p*<.05) higher centrality than cuts and depth.

**Betweenness**

The betweenness of each node was statistically significantly affected by concept type (*F*13, 126 = 5.14, *p* < .01, ήp2 = .35). Post hoc analysis revealed betweenness was statistically significantly higher (*p*<.05) in the high demand DT condition than the low demand condition. Bearing and contact had statistically significantly (*p*<.05) higher betweenness than all information pieces except merge and speed. Speed had statistically significantly (*p*<.05) higher betweenness than priority, cuts, depth, range and visual.

**Task Network analysis**

The type of tasks completed by the command team (same for high and low demand scenarios) centre around the generation of a tactical picture and knowledge of the priority contact being tracked based upon the integration of information from sonar and periscope (see figure 4). All subtasks facilitate an understanding of the vessels surrounding the submarine and the behaviour of the priority contact so that it can be safely tracked.



Figure. 4. *Task network diagrams for DT low and high demand scenarios. The task nodes and their connectivity were determined and verified by subject matter experts with operational RN sea experience.*

The tasks with the highest sociometric status were ‘detection of sonar contacts’ and ‘steer own vessel’ (see table 8). Sonar was used to inform own submarine manoeuvres, so that the priority contact could safely be tracked – which was the mission objective. The verification of task networks by subject matter experts provided the basis for the completion of task frequency analysis.

Table 8 **–** *Task network metrics for individual nodes returning to periscope depth scenarios*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Emissions | Receptions | Sociometric | Centrality | Betweenness |
| OOW brief | 1 | 0 | 0.03 | 14.74 | 0.00 |
| Raise Periscope  | 2 | 2 | 0.13 | 14.31 | 127.00 |
| 1st Sweep | 1 | 1 | 0.06 | 14.67 | 58.29 |
| Detect Close Visual  | 3 | 1 | 0.13 | 16.03 | 75.29 |
| First Reports | 2 | 2 | 0.13 | 16.57 | 61.04 |
| 2nd Sweep | 1 | 2 | 0.09 | 14.67 | 119.20 |
| Designate Visual  | 3 | 1 | 0.13 | 16.03 | 136.20 |
| ESM check | 1 | 1 | 0.06 | 14.67 | 71.71 |
| Submarine safe | 3 | 1 | 0.13 | 16.03 | 88.71 |
| Raise WT mast | 1 | 1 | 0.06 | 12.75 | 26.16 |
| Lower Periscope  | 3 | 4 | 0.22 | 18.56 | 226.30 |
| Surface | 0 | 1 | 0.03 | 39.11 | 0.00 |
| Classify visual contacts | 2 | 1 | 0.09 | 14.17 | 25.00 |
| Range/Course of visual  | 1 | 1 | 0.06 | 12.53 | 20.00 |
| Visually Identify Priority | 1 | 3 | 0.13 | 14.52 | 97.50 |
| Build visual picture | 3 | 1 | 0.13 | 13.52 | 37.00 |
| Dive | 1 | 1 | 0.06 | 27.41 | 0.00 |
| Detect contacts sonar | 3 | 5 | 0.25 | 23.65 | 247.80 |
| Close sonar contact | 1 | 1 | 0.06 | 18.80 | 0.00 |
| Designate sonar contact | 2 | 2 | 0.13 | 20.65 | 155.21 |
| Classify Sonar Contacts | 3 | 1 | 0.13 | 16.20 | 33.00 |
| Speed estimates | 1 | 1 | 0.06 | 13.77 | 0.00 |
| Identify sonar merges | 1 | 3 | 0.13 | 17.36 | 50.59 |
| Priority Contact sonar | 1 | 2 | 0.09 | 18.22 | 35.59 |
| Check cuts received | 3 | 2 | 0.16 | 18.68 | 153.91 |
| Build Sonar Picture | 3 | 2 | 0.16 | 17.78 | 81.18 |
| Generate Solutions | 2 | 3 | 0.16 | 18.45 | 59.82 |
| Merge visual and sonar  | 2 | 2 | 0.13 | 16.20 | 40.00 |
| Confirm tactical picture | 2 | 3 | 0.16 | 18.10 | 40.50 |
| Navigate/Steer vessel | 2 | 4 | 0.19 | 17.25 | 100.50 |
| Confirm Holding Priority | 2 | 1 | 0.09 | 15.52 | 54.50 |
| Refine solutions  | 0 | 1 | 0.03 | 19.42 | 0.00 |
| Complete Mission | 1 | 1 | 0.06 | 12.98 | 4.00 |

The frequency of task completion was statistically significantly affected by scenario demand (*F*1, 189 = 48.46, *p* < .01, ήp2 = .20) and task type (*F*20, 189 = 30.36, *p* < .01, ήp2 = .76). A statistically significant interaction (*F*20, 189 = 11.54, *p* < .01, ήp2 = .55) between scenario demand and task type was also observed. 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 (see table 9). The tasks of detecting, designating, classifying, generating speed estimates and gaining solutions from sonar as well as changes to own submarine parameters were completed statistically significantly (*p*<.05) more than all other tasks. Refinement of solutions was completed statistically significantly (*p*<.05) more than raising periscope, sweeping periscope and visual solutions (see table 8).

Table 9 **–** *Frequency of task completion DT scenarios*

|  |  |  |
| --- | --- | --- |
|  | DT |  |
|  | Low | High |
| Detect Sonar Contacts | 5.3 ± 2 | 13.2 ± 4.39 |
| Designate Sonar Contacts | 4.7 ± 1.34 | 10 ± 3.53 |
| Classify sonar contacts | 4.7 ± 1.57 | 8.6 ± 3.44 |
| Sonar speed estimates | 6.3 ± 1.83 | 9.2 ± 3.12 |
| Sonar course estimates | 1.9 ± 1.85 | 4.6 ± 3.72 |
| Check cuts | 1.9 ± 1.1 | 5.2 ± 3.43 |
| Sonar Merges | 2.5 ± 2.01 | 3.2 ± 1.69 |
| Sonar Solution | 5.4 ± 2.32 | 9 ± 2.87 |
| Refine Solutions | 3 ± 1.49 | 5.7 ± 3.37 |
| Change Submarine parameters | 5.9 ± 2.56 | 8.3 ± 2.98 |
| Raise Periscope | 1.4 ± 1.26 | 1.1 ± 0.32 |
| Complete Sweep | 2.5 ± 1.78 | 0.4 ± 0.7 |
| Detect visual contacts | 3.5 ± 1.9 | 1.6 ± 1.07 |
| Designate visual contacts | 2.9 ± 0.99 | 1.4 ± 0.84 |
| Classify visual contacts | 3 ± 1.05 | 1.7 ± 0.82 |
| Range visual contacts | 2.9 ± 2.92 | 1.2 ± 1.23 |
| Course estimates of visual | 1.3 ± 1.49 | 1.1 ± 0.57 |
| Visual solutions | 1.6 ± 1.07 | 0.6 ± 0.52 |
| Merge visual and sonar | 1.4 ± 1.35 | 0.7 ± 0.67 |
| Clear stern arcs | 0.1 ± 0.32 | 0.7 ± 0.82 |
| Final reports | 0 ± 0 | 0 ± 0 |
| Effect of demand | 48.46\*\*\* |  |
| Effect of task type | 30.36\*\*\* |  |
| Demand\*task | 11.54\*\*\* |  |

**Discussion**

The current work provides a detailed description of how a submarine control room functions when completing DT operations. The work builds upon a previous study examining the functioning of a command team during a returning to periscope depth (Stanton, 2014). The social, information and task networks presented in the current work highlight the complexities involved when completing DT submarine operations (Loft et al., 2016; Loft et al., 2013; Stanton, & Bessell, 2014 ; Huf et al., 2004; Kirschenbaum, 2001). The fact that tactical picture generation relies on information from disparate sources (e.g. periscope and sonar), that is required to be collated (by OPSO) and then integrated into a logical solution (by TMAs) is a good example of how cognition and SA are distributed across the control room (Stanton, 2014; Stanton, Salmon, & Walker, 2015; Stanton, 2016; Read, Salmon, Lenné, & Stanton, 2015). No single operator has ownership of all information or can complete all processing required without support of other command team members and technology. Therefore, it can be recommended that future control rooms should be designed to maximise relevant information flow between command team members and technology (e.g. multi-sensor information displays, co-location of operators sharing information and dynamic control room configurations (to meet demand). The current work provides evidence as to which command team members, information types and task types would benefit from alterations such as co-location (Stanton et al., 2010).

**Demand**

The total volume of emissions and receptions between operators in the command team significantly increased in the high demand DT condition. It appears that one way a submarine command team adapts to increased demand is by communicating more frequently, passing greater volumes of information and completing a larger number of tasks. The total emissions and receptions of different information nodes also increased, as did the total frequency of tasks completed. The fundamental perceptual capacities of humans mean that only a finite amount of information can be communicated (Baddeley, 2000). Moreover the technological limitations (e.g. radio channels and interfaces) and the command structure (e.g. who is permitted to talk to a particular operator) may limit the total number of communications that can occur (Stanton et al., 2015). Previous work has found that technological advancements (i.e. improved sensor capabilities) do not necessarily optimise performance if they are not effectively integrated (Dominguez et al., 2006; Roberts et al., 2015). Other media to support command team communication and sharing of information need to be explored (Stanton, Connelly, Prichard & van Vugt, 2002). An examination of how Royal Navy policy (e.g. hierarchy) might be optimized to share/reduce overall communication load, particularly in situations of high demand, may also be beneficial. An increase in automation might also have the potential to reduce communication load. The current work offers insight into which tasks and which operators may benefit from automation (Kaber, & Endsley, 2004; Knight, 2002). The introduction of automation in such a safety critical domain would require further investigation of its impact, but the current work provides a start point for this (Kaber, & Endsley, 2004; Knight, 2002).

**Social network analysis**

OPSO and SOC had the highest number of emissions and receptions (i.e. communications to and from others) of all operators in the control room. These operators are responsible for mediating between sonar data that is processed by the SOPs and building vessel solutions by TMAs. The high sociometric status and betweenness of OPSO and SOC demonstrates how critical these operators are in terms of tactical picture development. The fact that their sociometric status is greater than OOW demonstrates that the commanding officer is not explicitly involved in the development of the tactical picture (Dominguez, et al., 2006; Mansell, Tynan, & Kershaw, 2003; Chalmers, 2010). The greatest frequency of emissions and receptions in the social networks are between OPSO and SOC and their operators (SOPs and TMAs respectively). OPSO and SOC are required to manage and quality check the work of their operators. Workload management is particularly important in DT as operational mistakes may result in mission failure (Bateman, 2011). The low betweenness values of the TMAs and SOPs demonstrates that these operators are at the ends of the network. Reliance on OPSO and SOC to mediate between SOPs and TMAs might cause ‘bottlenecks’ in the information flow (Stanton, 2011, Salas et al., 2001; Carletta et al., 2000). The layout and structure of the command team might also be a contributing factor (Stanton et al., 2015). The co-location of operators who are highly reliant on each other for information exchange might have the capacity to optimise control room functionality.

Despite having the lowest number of emissions out of the command team (i.e. OOW, OPSO and SOC) OOW has the highest centrality of all operators in the control room. The OOW must orchestrate all members of the command team using the information from OPSO and SOC to direct the activities of PERI and SHC (Bateman, 2011; Loft et al., 2013; Huf, & French, 2004; Byers, 2014; Kirschenbaum, 2001). An interesting observation is the high number of communications between OOW and SOC, which is actually greater than the volume of communication between OPSO and OOW. OPSO is responsible for providing assistance to OOW as a tactical picture is compiled via the generation of TMA solutions, something critical during a returning to periscope depth (Stanton, 2014). This also seems to be occurring in the current DT scenarios. The OOW is also interested in the raw sonar data from SOC. This is because the OOW wants to be sure that the tracked contact remains in sonar range. The contact could be attempting to remain covert, hide behind the acoustic signature of other vessels, or outrun the submarine (Koubeissi, Pomie, & Rochefort, 2013; Xuan, & Li, 2006). The fact that the OOW is so central to the command team and is required to assimilate and interpret the tactical picture means that the OOW may benefit from sitting in the centre of their operators, something that could also be examined in future work.

**Information network analysis**

The information elements with the highest number of emissions and receptions are ‘bearing’ and ‘speed’. When operating at depth, the accuracy of passive sonar for facilitating tactical picture generation can be greatly affected by oceanographic conditions and background noise (Zarnich, 1999; Ogden, Zurk, Jones, & Peterson, 2011). In the DT scenario the command team began at periscope depth to visually identify the tracked vessel with a high degree of certainty (Bateman, 2011; Loft et al., 2013; Huf, & French, 2004). Once the submarine had dived the primary information that could be derived from passive sonar with relative certainty was ‘bearing’ and ‘speed’. This information is critical to the command team to ensure the tracked contact does not get lost, highlighted by the sociometric status value. The information element with the highest betweenness value was ‘contact’. Information such as ‘bearing’, ‘speed’, ‘range’ and ‘course’ relate to ‘contact’, both for the mission objective of tracking a contact and to maximise the safety of the submarine (Bateman, 2011; Jones, Steed, Diedrich, Armbruster, & Jackson, 2011).

The information elements ‘course’, ‘merge’ and ‘range’ have a similar amount of emissions and receptions. When tracking a contact, it is possible to remain at a shallower depth and raise periscope in a ‘duck-and-run’ fashion, at least initially, before diving to remain covert (Zarnich, 1999; Glosny, 2004; Bateman, 2011). The high sociometric status of ‘course’, ‘merge’ and ‘range’ was indicative of the tracking task. The sociometric status of ‘sonar’ information was higher than for ‘periscope’ and ‘visual’, highlighting that periscope is only used for a short period to maintain covertness. There is an effort to improve the sensor and algorithmic capabilities of passive sonar to maintain awareness of a contact, such as when transitioning from periscope depth to DT (Zarnich, 1999, Ogden, Zurk, Jones, & Peterson, 2011; Loft et al., 2013; Huf, & French, 2004). The manner in which information is connected and the importance of different types of information has the potential to inform future interface design, by providing an indication of which information should be most salient and where information overlap exists across different sensors (e.g. the capacity for ‘mash-displays’).

**Task network analysis**

The tasks most frequently completed typically relate to sonar (e.g. detection, designation and speed estimates). These tasks were completed significantly more frequently than tasks related to processing visual information (e.g. periscope sweep). This suggests that during DT the most commonly used sensor is sonar, despite having the option to ‘duck-and-run’, potentially to remain covert (Shar & Li, 2000; Stanton, 2014). The visual detecting, classifying and ranging of contacts is completed more frequently in the low demand DT condition than the high demand condition. The command team began the DT scenario at periscope depth and so it appears periscope was used more frequently, potentially at the start of the mission (in a ‘duck-and-run’ fashion) to gain a tactical picture. This was more prevalent in the low demand condition where there were fewer surface vessels present (Holt, Noren, Veirs, Emmons, & Veirs, 2009; Ogden et al., 2009; Bateman, 2011). An increase in the number of operationally active submarines is expected over the next two decades, increasing the likelihood of DT operations being completed (Bateman, 2011).

The detection of sonar contacts, generation of sonar speed estimates and designation of sonar tasks are the most frequently completed of all tasks. In the sub-group of visual tasks, detection and classification of contacts were still completed most frequently. It is important that detected contacts are classified so that the OOW can be sure that the tracked contact is clearly identified (Loft, 2016; Hunter et al., 2014; Loft, et al., 2013; Huf, & French, 2004; Li, 2009; Kirschenbaum, 2001). Making changes to own submarine parameters was also a task of high frequency, particularly in the higher demand scenario. This task reflects the need to keep the tracked vessel in range, by manoeuvring own submarine (Jones, Steed, Diedrich, Armbruster, & Jackson, 2011; Bateman, 2011; Duryea, Lindstrom, & Sayegh, 2008).

In many domains the design of control rooms will require a paradigm shift to manage the rapid advancements in technology that are predicated (Roco & Bainbridge 2003; Showalter, 2005; Roberts & Stanton, 2016; Negahdaripour, & Firoozfam, 2006; Santos, Teixeira, Ferraz, & Carvalho, 2008). Submarine control rooms for example may benefit from automating the collation of data from different sensors and instruments (e.g. visual vs. passive sonar), to supplement operator interpretation. The social network analysis can facilitate an understanding of which operators might best benefit from such task aids (e.g. an operator with particularly high sociometric status). The manner in which information is displayed in controls might also be optimised, particularly as the volume of data being processed increases. An example of this may be that the bearing at which sonar detections are encountered could be overlaid on a search periscope interface in the form of a ‘mash-display’. The information network analysis has the potential to optimise the design of interfaces and organisation of technology (Lee, & Kantowitz, 2005). Information elements that are strongly related (e.g. high betweenness) might be overlaid or positioned close to each other on an interface and information that is disparate (e.g. high farness) being positioned at greater distance. The current work has provided empirical evidence for clear delineations between submarine command team operators in terms of social, information and task network analysis when completing DT operations (Loft et al., 2016; Loft et al., 2013; Huf et al., 2004; Stanton, & Bessell, 2014; Kirschenbaum, 2001).

**Limitations and future research**

A limitation of the current work is that the cohort recruited were primarily novices with short training histories, completing simplified tasks, limiting the overall generalisability of the results. Previous work has highlighted substantial differences between novices and experts when completing contact tracking tasks (Loft, et al., 2016). However, the training provided to participants in the current study was substantially more extensive than what was provided by Loft and colleagues (8 hours vs. 17 minutes). It might be expected therefore, that the novice command teams in the current study provide a better representation of an expert command team. Participants were by no means ‘expert’ but rather ‘extensively trained novices’. This is supported by the fact that the results in the current study were comparable to an operational team completing training in a high fidelity simulator (e.g. sociometric status of OOW) albeit during the completion of a different scenario (Stanton, 2014). Also, the use of novice participants for command and control studies has been shown to be effective in previous research (Walker et al., 2014). It is likely that the results will not have absolute validity (e.g. be numerically comparable to expert teams) but will have relative validity (e.g. direction of effects) due to the submarine simulator and the entire study design (e.g. training materials, tasks and scenarios) being validated by subject matter experts and one of the teams tested being operational submariners. The fact that the operational command team result fitted within normal distribution curves offers further support for this. However, future research should aim to statistically compare Royal Navy teams to non-navy teams to ascertain the validity of the work, facilitating an understanding of which aspects can directly inform control room design and which aspects require higher fidelity testing. All recommendations (e.g. mash displays, co-location, central OOW and automation) from the current work should be considered with respect to its relative fidelity and that further work needs to be conducted which is more specific, potentially in high fidelity training simulators and/or at sea.

**Conclusions**

The current work provided an example of how the functioning of the submarine control room team may change as a result of demand – even when attempting to complete the same mission objectives. In the lower demand scenarios the OOW was able to use more periscope information, as it was safer to stay at periscope depth to track a contact. However, in high demand scenarios, the submarine was forced deeper earlier, due to safety concerns. Future work should aim to examine if operator roles within a command team can be more flexible and mission/demand dependent. An example of this is that when periscope is not available (i.e. submarine is not at Periscope Depth) a periscope operator could optimise sonar data. The manner in which information is used also changes based upon the operation type. The commanding officer is more interested in raw sonar/periscope information concerning key parameters of a tracked contact during a DT operation, whereas in a returning to periscope depth scenario the focus is on TMA solutions derived from sonar. Future research should examine whether interfaces can display information in a form that is most relevant to the current mission objective, potentially merging different sensors and presenting the most pertinent information.

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