**Macrocognition in Submarine Command and Control: A Comparison of three Simulated Operational Scenarios**

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**Abstract**

Submarine command and control operations are not well understood, but are an exemplar of macrocognition. For the first time, this study compares three operational scenarios in a simulated submarine control room: Returning to Periscope Depth (RTPD), Inshore Operations (INSO), and Dived Tracking of Contact (DT). The Event Analysis of Systematic Teamwork (EAST) method was used to model macrocognition by way of social, task, and information networks. Results indicate that the composition of the networks differed significantly depending upon operation type and demand. The statistical differences reveal how macrocognitive processes such as situation assessment, coordination, and problem detection are context dependent and drive the attainment of team knowledge to suit operational requirements. The Officer of the Watch consistently had the highest centrality of all operators, highlighting the importance of this operator in utilising team knowledge to inform tactical decisions. Implications are discussed alongside suggestions for future work.

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

**General audience summary**

A team is a collection of individuals working together towards a higher goal, often with the support of technologies to achieve such aims. The processes, referred to as macrocognition, which facilitate teams of individuals working together is complex and not well understood. Submarine command and control is generally not well explored in the literature because access is often not possible. The current paper aimed to model the macrocognition of submarine command and control by comparing three operational scenarios: Returning to Periscope Depth (i.e., getting the submarine from safe depth to periscope depth), Inshore Operations (i.e., costal protection and reconnaissance), and Dived Tracking of Contact (i.e., tracking another vessel – either on the surface or subsurface). This study explored how macrocognitive processes (such as situation assessment, coordination, and problem detection) differ depending upon operational requirements. The Event Analysis of Systematic Teamwork (EAST) method was used to model macrocognition by way of social, task, and information networks. The networks were generated from the transcripts of ten teams of eight novice individuals that were trained to be representative of a submarine command team in a submarine control room simulator. The network metrics were statistically compared to examine differences in their composition that reveal context dependent differences in macrocognitive processes. Results indicated that junior operators in the command team were responsible for situation assessments, which was supported by senior command team members via the completion of co-ordination and problem detection processes. The most senior members of the command team complete adaption based processes to rectify mistakes or improve the tactical picture which is the summation of team knowledge. Insights are provided into future research ideas and recommendations to improve future submarine command and control operations.

**Macrocognition in Submarine Command and Control: A Comparison of three Simulated Operational Scenarios**

A team is a collection of individuals who interact with varying levels of interdependence for the achievement of shared goals (Cooke, Gorman, & Kiekel, 2008; Salas, Shuffler, Thayer, Bedwell, & Lazzara, 2015). There is often a reliance on supporting technologies to enable team-based processes, and facilitate adequate interdependence (Letsky, Warner, Fiore, Rosen, & Salas, 2007). A sociotechnical system is defined as the interaction of human operators and technology, often with growing interdependence in pursuit of purposeful, goal-directed behaviours (Walker, Stanton, Salmon, & Jenkins, 2009). The effective engineering of complex sociotechnical systems to maximise collaborative activity requires an understanding of macrocognition as it naturally occurs in complex decision making environments (Klein, Ross, Moon, Klein, Hoffman, & Hollnagel, 2003). A submarine control room relies on effective interaction between multiple technological and human agents for optimal performance. It is an excellent example of a complex sociotechnical system (Shattuck & Miller, 2006; Stanton, 2014; Walker et al., 2009). Submarine control rooms therefore, provide an interesting context to examine macrocognition (Driskell, Salas, & Driskell, 2017; Letsky et al., 2007).

**Macrocognition**

The field of Naturalistic Decision Making (NDM) attempts to understand how people make decisions in applied environments rather than in artificial laboratory settings (Klein, 2015). Macrocognition is defined as a collection of processes or cognitive functions that are performed in complex naturalistic decision-making environments. Providing a framework for understanding processing beyond the singular level (Fiore, Smith-Jentsch, Salas, Warner, & Letsky, 2010; Klein et al., 2003). Decision making in naturalistic environments relies on experience-based pattern matching, therefore a key challenge for decision makers is making sense of the conditions rather than choosing between multiple options (Klein, 2015). The NDM view of macrocognition proposes a set of emergent functions and processes (e.g., situation assessment, co-ordination, and problem detection) that describe how complex sociotechnical systems operate (Klein et al., 2003; Schraagen, Klein & Hoffman, 2008).

There is debate regarding the composition of macrocognitive processes and how they might best be measured (Wildman, Salas, & Scott, 2014). The team cognition perspective of macrocognition emphasises the coordinating mechanisms that facilitate collaborative activity amongst individuals to build, and exchange knowledge in service of higher order team goals (Fiore et al., 2010). This divergence in perspectives is not necessarily problematic (e.g., co-ordination is listed as a macrocognitive process in the NDM literature) as it is acknowledged that currently proposed macrocognitive functions will likely change as research in the field progresses (Klein et al., 2003). A frequent criticism of NDM research is that explanations tend to be vague regarding the underlying process governing behaviour and lack formalisation due to an absence of measurable parameters (Thomson, Lebiere, Anderson, & Staszewski, 2015). Therefore, a key challenge for understanding macrocognition is the capacity to quantify such process without losing the essence of the NDM perspective via over simplification of complex natural environments (Klein et al., 2003; Wildman et al., 2014).

An eloquent description of team cognition research describes two separate approaches to team cognition as being in the head or between the heads (Cooke et al., 2008). Understanding the processes that drive and facilitate the switching of knowledge between the internalised individual team members to an externalised team construct, and vice versa, is regarded as an investigation of macrocognitive processes (Cooke et al., 2008; Fiore et al., 2010; Letsky et al., 2007; Wildman et al., 2014). It may not be possible to examine all macrocognitive processes from this perspective; nevertheless, it is important to encourage research at the macrocognitive level of description (Klein et al., 2003). It has been proposed that analysis of team communication allows for direct observation of cognition occurring between the heads (Cooke et al., 2008).

**Submarine Command and Control**

A submarine control room is analogous to a human mind, containing a range of sensors that act as the ears (sonar), eyes (periscope), and vestibular system (gyroscopes) of the submarine (see Figure 1). Human cognition relies on Working Memory (WM), a limited capacity system responsible for the temporary storage and manipulation of task relevant information from different sensory modalities, and internal memory constructs (Baddeley, 2000; Radvansky, 2017). Understanding how submarine command teams make sense of their environment is challenging due to the complexities involved in the generation and development of a tactical picture by multiple operators (Dominguez, Long, Miller, & Wiggins, 2006; Hicks, Stoyen, & Zhu, 2001; Stanton & Roberts, 2017). As with WM, the capacity of the command team is limited, and synthesis of information from different sensors relies on effective teamwork and communication. Such processes can become the limiting factor in determining workload of the team, rather than the work itself (Carletta, Anderson, & McEwan, 2000; Salas, Burke, & Samman, 2001). The cognitive capacity of individual operators is one factor that will determine the capacity of the team, via the data-information-knowledge cycle that creates internalized knowledge (Fiore et al., 2010). However, the between the heads macrocognitive processes guide team knowledge building that is the focus of the current work.

In a submarine control room, environmental sound propagation is received by sonar arrays which is processed and represented on an interface for sonar operators to monitor (Bateman, 2011; Shar & Li, 2000; Zarnich, 1999). The sonar operators interactions with sonar interfaces facilitates the conversion of sonar data to information as part of individual knowledge building processes (Fiore et al., 2010). The periscope operator performs similar duties using visual data and the ship control operator comprehends processed gyroscopic data concerning own submarine parameters (Stanton & Roberts, 2017). This provides insight into the technological aspects of the command system including technology-to-technology information transition, and technological support for the individual knowledge building processes. However, it does not reveal the processes undertaken by the command team to build team knowledge – essential macrocognitive processes are not revealed.

The development of new sensor, technology, software algorithms, and architecture has the potential to optimise submarine control rooms (Wang, Chen, Blasch, Lynch, & Pham, 2011; Zarnich, 1999). The design and operation of control rooms are primed for revolutionary changes across many domains to optimise productivity and reduce costs (Roco & Bainbridge 2003; Santos, Teixeira, Ferraz, & Carvalho, 2008; Showalter, 2005; Stanton, Harris, & Starr, 2016). However, such advancements are routinely implemented without rigorous assessment of their impact on performance from a sociotechnical (Stanton et al., 2009, Walker et al., 2009) or macrocognitive perspective (Keyton & Beck, 2010; Klein et al, 2003; Wallace & Hinsz, 2010). The purpose of this article is to quantify information exchange between command team operators across a variety of operation types, with differing levels of demand. The demands imposed by the task environment have the potential to impact performance due to increases in cognitive load at the level of the individual, and the team (Driskell et al., 2017). The data presented in the current paper has been published previously for distinctly different purposes (i.e., a detailed description of each operation type), employing a different statistical approach (see Roberts, Stanton & Fay, 2017; Stanton, Roberts, & Fay, 2017).

**Method**

**Participants**

Ten teams of eight individuals (80 participants in total) were recruited opportunistically using posters and word of mouth. A total of 71 males and 9 females participated with an age range of 18-55 (*M* = 26.83, *SD* = 8.69) from a variety of backgrounds primarily including undergraduate students and graduate recruits from defence companies. One team were submariners from the British Royal Navy. The use of novice participants for studies into command and control has been justified previously (Walker, Stanton, Salmon, Jenkins, Rafferty, & Ladva, 2010). The role of the Officer of the Watch (OOW) was performed by one of the experimental team in all teams apart from the Royal Navy team (this was necessary as it would not be possible to train the OOW role within a short amount of time). Participation in the study was voluntary. 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 ComTET team built a submarine control room simulator that is based upon a currently operational Royal Navy (RN) submarine. A full description of the building process and the simulator capabilities is provided by Roberts and colleagues (2015). The simulation engine used was Dangerous Waters (DW) software, a naval warfare simulation game developed by Sonalysts Combat Simulations. The software featured networked workstations. Two Sonar Operator stations (SOP), two Target Motion Analysis stations (TMA), a Sonar Controller station (SOC), an Operations Officer station (OPSO), a Periscope station (PERI), a Ship Control (SHC) station, and an Officer of the Watch station (OOW). All communications in the simulator were recorded by 10 web-cameras, 2 high-resolution video cameras, 2 ambient microphones, and the installation of recording software to capture any transmissions (using headsets and microphones) over the five channel communication network.

A set of operational scenarios were selected and designed with input from subject matter experts (SMEs) to be representative of real high and low demand operations. Routine Submarine operations are split into three broad categories. During a Return to Periscope Depth (RTPD), submarines predominantly rely on passive sonar to detect vessels and enable tactical picture generation (Bateman, 2011; Shar & Li, 2000; Stanton, 2014; Zarnich, 1999). Increasingly, submarines are being used to complete Inshore Operations (INSO), performing duties such as costal protection and reconnaissance (Bateman, 2011; Duryea, Lindstrom, & Sayegh, 2008). The Dived Tracking (DT) of a contact requires submarine command teams to track contacts whilst submerged at great depth whilst attempting to remain undetected (Bateman, 2011; Byers, 2014). Scenario demand was manipulated by number of contacts detectable in the scenario, contact behaviour (e.g., speed and course changes), and area of operation. In all scenarios the behaviour of the contact vessels were pre-determined, each scenario lasted for approximately 45 min.

**Design**

In general, the study employed a 3 x 2 x 9 mixed design. The independent variables were scenario type (RTPD, DT, and, INSO - within subjects) scenario demand (low and high - within subjects), and operator role (between subjects). However, the information network analysis employed a 3 x 2 x 12 mixed design (12 information nodes) and the task network analysis employed a 3 x 2 x 14 (14 task nodes). The dependent variables were static adjacency matrices (social, information, and task) derived from the communications that took place between operators within the command team.

**Procedure**

Participants attended the submarine simulator for two full days (8am – 5pm). On the first (training) day, informed consent was attained from participants and team roles were randomly assigned. Participants then spent the day watching a number of video tutorials. Each tutorial lasted approximately 45 min. The morning contained general submarine command team training (e.g., awareness of sensors, objectives, and communication structure), whilst the afternoon included workstation specific tutorials (e.g., operation of interfaces for individual task completion), and practice completing scenarios as a command team. Regular breaks and were provided across the training day and a number of experimenters with extensive DW experience were present to answer questions and provide training support. 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 and generate speed estimates) as outlined by SMEs when developing the training package. If during the final training scenario a command team had not 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 by SMEs.

On the second (testing) day, participants first completed a practice scenario as a command team. Performance was monitored by experimenters to ascertain that all tasks were being executed correctly. Participants then completed all six testing scenarios. Each team of eight participants completed all scenarios, occupying the same positions in the command team. Participants were informed that the first scenario would begin – all recording devices were started and a verbal time stamp was read aloud for synchronization purposes. Then the OOW briefing began. 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. At the end of the sixth scenario participants were provided with a full debrief and thanked for participating.

**Analysis of Data**

The effective measurement of macrocognition is difficult due to the wide range of different processes to be examined and the huge array of measurement techniques (e.g., self-reports, relatedness ratings, and interviews) available for measuring the same process (Letsky & Warner, 2008; Wildman et al., 2014). The rich data captured in communications between teams is not just a lens to examine team cognition, but rather team communication is cognitive processing at the level of the team (Cooke et al., 2008). Communications between team members are viewed as being amongst the most reliable, rich, and unobtrusive methods for understanding macrocognition (Fiore et al., 2010; Letsky & Warner, 2008; Wildman et al., 2014). When team communication data is used as the primary analysis pathway, the method of data collection (e.g., interviews vs. communications transcripts), and analysis conducted (e.g., content analysis vs. pathway analysis), should facilitate the aims of the research and the processes(s) of macrocognition being investigated (Wildman et al., 2014). Nevertheless, there is a drive to uncover novel measures of macrocognition to facilitate empirical research (Letsky & Warner, 2008).

In the current work, the analysis of data used is a new shortened form of Event Analysis for Systemic Teamwork (EAST: Stanton, Barber, & Harris, 2008). This approach has been used to model submarine command and control (Stanton, 2014), and analyse sociotechnical systems in numerous other domains (Houghton et al., 2006; Stanton & Harvey, 2017; Stewart et al., 2008). EAST uses raw data of video and audio recordings of communications within the command team (Keyton, Beck, & Asbury, 2010) which were transcribed to generate three networks examining; communications between agents in the system, the type of information used by agents, and the tasks completed by agents in the network. The networks were processed using AGNA software (version 2.1.1 – a software program for computing the Social Network metrics). AGNA was used to compute whole network metrics (e.g., density, diameter, and cohesion) and nodal metrics (e.g., sociometric status and centrality). A detailed description of metrics used is provided by Stanton (2014). 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 by listening to audio to ascertain what particular tasks were performed. This was completed by SMEs before frequency counts of all tasks were completed. The social network approach has been highlighted as having great potential as a tool for measuring team cognition, particularly from the perspective of transactory memory systems (Wildman et al., 2014). However, EAST is highly novel as it takes network examination of communication a step further, not just networking the social interactions, but also the connectivity of information communicated, and tasks completed from a macrocognitive perspective (i.e., team information and team tasks).

A benefit of the network analysis approach to information is that it enables the calculation of network metrics that quantify the social, information, and task network composition between scenario types and levels of demand, affording empirical investigation through statistical comparison. This is a key requirement for the advancement of macrocognition theory (Letsky & Warner, 2008; Thomson et al., 2015)**.** The statistical aggregation method has been criticised for averaging individual team members scores (e.g., self-report mental model ratings) to represent a team score based upon similarities between individuals (Wildman et al., 2014). However, the metrics derived from the EAST analysis are based upon network connectivity that represents the team information transitions, content, and relevance to task completion.

The data was assessed to check it met the requirements (e.g., distribution and homogeneity) for parametric analysis to be conducted. 3 x 2 x 9 mixed analyses of variance (ANOVA) were conducted to examine the effect of scenario type, scenario demand, and operator role on social node metrics. 3 x 2 x 14 mixed ANOVAs were conducted to examine the impact of scenario type, scenario demand, and information type on information node metrics. 3 x 2 repeated measures ANOVAs were conducted to examine differences between scenario type and scenario demand for total network metrics (social and information). To examine differences in the frequency of task completion between scenarios different scenarios of high and low demand 3 x 2 x 12 mixed ANOVAs were conducted. Post hoc pairwise comparisons were conducted to examine main effects. To account for multiple post hoc comparisons the Bonferroni correction method was used (α = 0.05/number of comparisons). All statistical analysis were conducted using IBM SPSS v21. Due to the large volume of statistical analysis completed, only pertinent results (and networks) are presented. The results are presented in order of social, information, and task network analysis. In each section an overview of the statistical comparisons of the total networks and nodal metrics are presented, along with insights into the contributions to understanding macrocognition afforded by EAST.

**Results**

**Social Network Analysis**

Statistically significant differences in emissions by an operator were observed depending on role type *F*(8, 81) = 72.73, *p* < .001, partial ηp2 = .88, the interaction of scenario and role *F*(16, 162) = 3.24, *p* < .001, ηp2 = .24, and the interaction of scenario, demand, and role *F*(16, 162) = 9.74, *p* < .001, ηp2 = .49. This indicates that the co-ordination within the command team is different depending upon the particular type of operation being completed and level of demand. In Table 1 and Figure 1, it can be seen that OPSO and SOC had the largest number of communications across all scenario types. Typically, OPSO and SOC had more emissions and receptions than all other operators (except OOW). The largest number of communications by the SOPs are to and from SOC; similarly, the largest amount of emissions and receptions from the TMAs are to and from OPSO. SOC and OPSO are responsible for quality checking the work of the SOPs and TMAs respectively. Therefore, the strengths of these connections provide examples of how the detection of problems are completed within the command team to ensure that inappropriate sonar detections, and target motion analysis solutions are minimised. Detection of errors at this stage stops incorrect information being integrated into the tactical picture, which could lead to inappropriate tactical decisions being made later in the scenario (e.g., OOW manoeuvres submarine to avoid contacts that does not exist).

Inspection of the social networks also reveals that OPSO and SOC are two of the most strongly connected operators, particularly during the DT high demand scenarios (see Figure 1c). A second responsibility of OPSO and SOC is the synthesis of information from different sensors, often using pattern matching to identify relevant information merging or errors. This is a further example of team co-ordination but also workload delegation (i.e., directing which contacts the SOPS and TMAs should process further). It appears that OPSO and SOC are the primary operators directing such processes. Despite the TMAs relying on the SOPs for information regarding sonar profiles, these operators do not directly communicate. Therefore, knowledge held in the minds of the SOPs is communicated to SOC, providing an example of sub-group (i.e., sonar operators) team knowledge generation. Once sonar team knowledge has been verified and potential problems detected, SOC communicates this information to OPSO, so that it can be adequately distributed to the relevant TMA operator tasked by OPSO to work on a particular contact. The fact that SOC and OPSO control the flow of information between the sonar team and the picture compilation team allows these operators to co-ordinate the workload of the SOPS and TMAs to best suit the requirements of the command team (e.g., prioritise contacts). It appears that the macrocognitive processes of error detection and workload co-ordination simultaneously co-occur in this instance (i.e., if the internalised knowledge of SOPs and SOC do not align, and so require correction), potentially revealing why macrocognitive processes are difficult to quantify. In practical terms, it may also be problematic that the connection between SOC and OPSO is a potential bottleneck in the network. The flow of information between the SOPS and TMAs is entirely dependant on communication between SOC and OPSO as information brokers. Whilst this facilities early error detection and co-ordination of resources it may also limit productivity, particularly if OPSO and SOC are engaged in completion of additional macrocognitive processes.



**Figure. 1.** Social network diagrams for RTPD low demand, INSO high demand, and DT high demand scenarios. *Note.* In the RTPD low scenario the communication between SOPs (black nodes, Figure 1a) is at its highest as co-ordination of the situation assessment is driven in a bottom-up fashion. However, communication between the SOPs (grey nodes, Figure 1c) are lowest during the DT high demand scenarios, where co-ordination of the situation assessment is driven in a top down fashion by OPSO and SOC. The increased number of communications between OPSO and SOC (black nodes, Figure 1c) in the DT high demand scenarios further highlights this. However, during the INSO high demand scenarios, communication between OPSO and SOC (grey nodes, Figure 1b) are at their lowest, even lower than the low demand RTPD scenario. This reveals how co-ordination of team knowledge is flexible and operationally dependant as the number of communication PERI (black node, Figure 1b) has with OOW and OPSO is at its highest during the INSO scenario when visual data is more prevalently utilised.

In each of the networks (see Figure 1), differences were observed in the average volume of emissions and receptions between nodes (indicated by grey and black nodes), providing insights into differences in macrocognitive processes due to scenario type and demand. Communication between the SOPs is highest during the RTPD low demand (Figure 1a) scenario and lowest during DT high demand (Figure 1c) scenario. The communication that occurs between these operators captures the process of situation assessment, to understand the external environment and ensure that all basic sonar duties are completed. During a RTPD it is critical that the command team has awareness of all contacts around the submarine, as once a shallower depth the potential of collisions with surface vessels increase. The SOPS still liaise with SOC during this process (e.g., for permissions to designate contacts), however, during a RTPD the process is driven in a bottom-up fashion. In this type of scenario, the SOPs are the ears of the submarine, the only usable sensor, and so must check all bearings to inform a complete situation assessment of the environment. However, during a DT the senior members of the command team have internalised knowledge (i.e., intelligence received during brief) that a particular contact of interest is required to be tracked from deep. In this type of scenario the situation assessment is driven in a top-down fashion. SOC directs the SOPS activities to ensure that priority contacts are monitored, rather than generating a complete surface tactical picture. This is further validated by observation that communications between SOC and OPSO were greater during the DT scenarios compared to the RTPD, and INSO scenarios (see Figure 1a-c). Seemingly due to the fact that the construction of a tactical picture requires greater co-ordination by higher command (e.g., OPSO and SOC) during a DT to inform the work of the operators individual data acquisition (i.e., sonar derived speed estimates and TMA solutions of priority contacts). This highlights how empirical examination of communications facilitates a greater understanding of how operational requirements change the manner in which macrocognitive processes occur (i.e., top-down vs. bottom up).

Statistically significant differences in the sociometric status of an operator were observed depending on role type *F*(8, 81) = 80.53, *p* < .001, ηp2 = .89, the interaction of scenario and role *F*(16, 162) = 2.49, *p* = .002, ηp2 = .20, and the interaction of scenario, demand, and role *F*(16, 162) = 9.44, *p* < .01, ηp2 = .48. The sociometric status of PERI is statistically significantly (*p* <.01) higher during the INSO scenarios compared to both RTPD, and DT (see Table 1). The periscope operator is required to complete a situation assessment (similar to SOPs) using visually derived data. The increased sociometric status of this operator during an INSO highlights how the focus of situation assessment changes depending on operational requirements. This is due to the fact that during INSO scenarios the submarine is operating at shallower depths, where there is a high risk of collision with surfaces vessels. Periscope is the best sensor for ensuring submarine safety (i.e., definite visual vs. ambiguous sonar), so the command team rely on visual information more, resulting in the high sociometric status of PERI. The socometric status of PERI is greater in the high demand INSO scenario indicating that as demand increases an even greater reliance is placed on visual data to ensure submarine safety (see Table 1). The change in focus between different sensors to inform situation assessment is further highlighted by the decrease in sociometric status of SOC during the INSO scenarios, with a statistically significant decrease (*p* <.01) observed comparted to the RTPD, and DT scenarios. The process of information co-ordination is driven by OPSO, with a large increase in the volume of communications between OPSO and PERI observed during the INSO scenarios (see Figure 1c).

**Table 1**

Mean (and standard deviation) social network metrics for individual operators

|  |  |  |  |
| --- | --- | --- | --- |
|  | Emission | Sociometric  | Centrality |
|  | Low | High | Low | High | Low | High |
|  | RTPD |  |  |  |  |
| OOW | 111.20 (32.44) | 117.00 (45.60) | 24.30 (7.46) | 26.44 (10.72) | 5.61 (0.35) | 5.77 (0.35) |
| OPSO | 158.20 (55.27) | 204.20 (52.97) | 39.99 (11.14) | 51.11 (12.52) | 5.40 (0.30) | 5.31 (0.24) |
| SOC | 141.00 (46.39) | 193.20 (54.35) | 35.60 (10.99) | 48.13 (12.91) | 5.78 (0.50) | 5.68 (0.22) |
| SOP1 | 59.20 (34.98) | 64.50 (35.02) | 14.30 (7.58) | 17.18 (9.65) | 4.12 (0.34) | 4.12 (0.14) |
| PERI | 33.70 (9.19) | 25.80 (17.19) |  7.55 (1.71) |  5.84 (3.85) | 4.94 (0.47) | 5.07 (0.70) |
|  | INSO |  |  |  |  |
| OOW | 112.90 (31.60) | 133.00 (32.08) | 26.94 (6.13) | 32.34 (6.36) | 5.86 (0.37) | 5.94 (0.49) |
| OPSO | 172.20 (24.43) | 192.80 (26.64) | 43.57 (5.03) | 48.56 (7.23) | 5.79 (0.37) | 5.66 (0.23) |
| SOC | 88.20 (37.98) | 151.80 (38.91) | 22.73 (7.75) | 38.11 (9.49) | 5.29 (0.77) | 5.57 (0.35) |
| SOP1 | 37.90 (07.96) | 54.10 (19.60) | 11.65 (3.52) | 15.04 (5.29) | 3.91 (0.12) | 3.99 (0.13) |
| PERI | 104.60 (50.79) | 105.30 (46.21) | 19.94 (9.42) | 21.15 (8.04) | 4.95 (0.57) | 5.21 (0.45) |
|  | DT |  |  |  |  |  |
| OOW |  94.40 (14.65) | 114.89 (18.50) | 22.86 (3.73) | 27.89 (4.85) | 5.87 (0.38) | 6.21 (0.25) |
| SOC | 131.70 (52.72) | 177.50 (35.88) | 32.23 (11.56) | 45.18 (8.52) | 5.65 (0.15) | 5.28 (0.14) |
| SOP1 | 45.20 (27.66) | 62.67 (21.09) | 12.25 (6.96) | 16.02 (6.64) | 3.88 (0.23) | 3.99 (0.33) |
| PERI | 48.80 (16.92) | 32.56 (16.67) | 10.22 (3.69) |  6.75 (3.60) | 5.26 (0.26) | 5.00 (0.33) |

 *Note*. Pertinent differences and similarities between operators due to scenario type and demand are highlighted in black

Statistically significant differences in the centrality of an operator were observed depending on role type *F*(8, 81) = 319.92, *p* < .01, ηp2 = .97 and the interaction of scenario and role *F*(16, 162) = 2.53, *p* = .003, ηp2 = .20. The centrality of OOW is statistically significantly higher (*p* <.01) than most operators regardless of operation type or demand (see Table 1). The OOW is the operator responsible for making all tactical decisions in the command team, utilising knowledge generated by the command team presented as a tactical picture to complete mission objectives and ensure submarine safety. The centrality of OOW remains high despite not always having the greatest number of emissions or sociometric status. This is due to the fact that the OOW communicates with all members of the command team to ensure that team knowledge is effectively utilised to inform executive decision making. The OOW is also responsible for planning and promoting adaption to operational demands. The OOW primarily directs adaptive and planning based processes via OPSO and SOC as co-ordinating operators within the command team, simultaneously using the input of these operators to detect problems with the tactical picture. It is for these reasons that the strength of communications from OOW to OPSO, and SOC remains consistent across all scenarios (see Figure 2). The strength of connection between OOW and PERI is only high during an INSO where OOW assumes some of the co-orientating responsibility of periscope co-ordination to ensure submarine safety. The OOW acts as binding node in the command team connecting all operators and sub-groups of operators (including SHC) to complete submarine manoeuvres to facilitate adaption, and re-planning based upon operational requirements.

**Information Network Analysis**

The structure of the information networks was statistically significant different depending on scenario demand and operation type. This included a significant effect of demand on the total number of edges *F*(1, 9) = 8.20, *p* = .019, ηp2 = .48 and emissions *F*(1, 9) = 41.68, *p* < .001, ηp2 = .82. A significant effect of operation type on total number of edges *F*(2, 18) = 3.70, *p* = .045, ηp2 = .29 and network diameter *F*(2, 18) = 4.98, *p* = .019, ηp2 = .20 was also observed. The changes in composition reflected differences in macrocognitive processes based upon the type of information most prevalently used by the command team, and that the manner in information was communicated (i.e., its connectivity) differed depending on operational demand. The first observation is that the command teams exchanged a greater volume of information (emissions) in the high demand scenarios and that the information exchanged was more connected (edges). Indicating that during the high demand scenarios, the greater volume of information transition between command team members was less structured (i.e., the order of information was more sporadic). One explanation for such differences is that OPSO and SOC are more involved in planning adaptive responses with OOW, resulting in a reduced capacity to co-ordinate the exchange of information between the SOPs, TMAs, and PERI. Therefore, when the these operators had an opportunity to communicate with SOC and/or OPSO they attempted to communicate as much information as possible, which had potentially been internalised and stored for a greater period of time than during low demand conditions. This would result in information being less structured in the way it is communicated (i.e., less adherence to standard communication protocols) to cope with the fact that OPSO and SOC have less time dedicated to information brokering between different operators completing situation assessment processes. This appears to be further supported by the fact that the low demand scenarios revealed a more structured pattern of information exchange with less nodes, less edges, and less emissions but relatively high cohesion. This is verified by the fact that the number of edges were statistically significantly (*p* <.05) lower in the low demand scenarios, indicating reduced connectivity between information nodes. This suggests that during the low demand scenarios teams were operating within capacity, exchanging information in the manner that had been trained (i.e., standard operating procedures vs. adaptive information transition).

The second observation is that the volume (emissions) and connectedness (edges) of information was statistically significantly different depending on scenario type (see Figure 2). This suggests that differences existed in the manner that co-ordination occurs within the command team based on operational requirements. An example of this is that the differences observed between the high and low demand RTPD scenarios (emissions = 486.80, nodes = 1.20, edges = 57.30), was much less than in the INSO (emissions = 1934, nodes = 2.90, edges = 194.20) and DT scenarios (emissions = 1284.47, nodes = 4.98, edges = 116.73). The RTPD scenario is the most standardised in terms of operation completion, the command team is looking for an area where there are less contacts rather than being required to navigate to a particular point (INSO), or track a particular contact (DT). Therefore, the communication between operators that contributed to the generation of a tactical picture through situation assessment processes to facilitate decision making by the OOW required less co-ordination and/or problem detection. This resulted in a lower volume of information that was less connected. The level of uncertainty is often higher during a DT/INSO and the completion of tasks is more linear during a RTPD (i.e., there are fewer tactical options available). It appears therefore, that the DT and INSO scenarios required the completion of more planning and adaption based processes. This resulted in a greater volume of information that was more connected.



**Figure 2.** Information Network Diagram for RTPD low demand scenarios. *Note:* The low demand scenarios contained fewer information nodes that are less connected compared to the high demand scenarios. Indicating that less information is communicated in a more structured manner during the low demand scenarios. The information node with the highest centrality across all scenarios types was contact (grey node) as this information is connected to the greatest number of additional information nodes. This is due to the fact that knowledge of contacts presence and behaviour underpins all activities undertaken by the command team. Information such as bearing, speed, and range (black nodes) typically have similarly high socimetric status across all scenarios as this information is critical for informing knowledge of contact behaviour. However, there are differences in the prevalence of information between scenarios. Information such as periscope and visual information (checked node) is communicated more frequently during the INSO than RTPD scenarios.

A third observation is that certain information nodes remained critical regardless of operation type or demand. For example, in all scenarios contact had statistically significantly (*p* <.01) higher centrality than most other information nodes, and bearing and course typically had significantly higher (*p* <.01) sociometric status than all other information nodes. This appears to indicate that the communication of this type of information is critical for the completion of all macrocognitive processes, regardless of demand, scenario type, or operational strategy (i.e., bottom-up vs. top-down). This reveals that regardless of the operation being completed, the command team are predominantly interested in knowledge of contacts surrounding own submarine, and that frequently the only definite information a command team has regarding contacts is their bearing. Moreover, regardless of the sensor that is most frequently used for situation assessment (e.g., periscope vs. sonar) the command team the information provided by these sensors relates to the location (i.e., bearing) of surrounding vessels (i.e., contacts). The attainment of this knowledge is further facilitated by the completion of own submarine manoeuvres based upon situation assessment completed by SHC, co-ordinated by OOW to maximise tactical advantage and the making of effective decisions with regard to mission objectives and submarine safety.

A final observation from the information network analysis involved examination of the differences between information nodes that occurred across different scenarios types. In general, this analysis reveals that that despite certain types of information appearing to consistently support macrocognitive process (e.g., knowledge of contacts, bearing, and course), certain information nodes are more prevalent in different scenario types, revealing how macrocognitive processes occur differently depending on operational context. An example of this is that during the INSO scenarios the information periscope and visual was statistically significantly (*p* <.01) more prevalent and more connected than in the RTPD scenarios (see Figure 2). This is because during an INSO the command team utilises periscope data more frequently as part of a situation assessment process. This type of information permits a higher degree of certainty (i.e., compared to passive sonar) and so visual information becomes much more within the information networks generated by the command teams.

When examining the DT scenarios, information such as merge and course (particularly in high demand), had higher sociometric status compared to INSO and RTPD scenarios. During a DT scenario, the command team is co-ordinated to develop detailed and up to date knowledge of the course and speed of the to-be-tracked contact, and the merging of all relevant information that facilitates this primary mission objective, which is tracking. It is for similar reasons why information such as solution had (*p* <.01) significantly higher sociometric status in the RTPD scenarios than the DT scenarios, as the command team is more focused on solutions for all contacts to ensure a safe area for returning to periscope depth, rather than a focus on one contact during a DT scenario. Interestingly, speed is amongst the most prevalent information nodes across all scenarios in terms of emissions, with no significant differences observed between scenarios in terms of emissions. However, speed had statistically significantly (*p* <.01) higher sociometric status during the DT scenarios compared to the RTPD scenarios. This is because the vessel may try to evade the submarine (i.e., increase speed) and so knowledge of the to-be-tracked contacts speed was critical to the command team. Situation assessment (e.g., speed estimates from sonar), coordination (e.g., integration into tracked contact solution), and problem detection (e.g., errors in speed estimates) tasks would therefore have been completed to attain accurate knowledge of the contacts speed.

**Task Network Analysis**

The structure of the task networks was different across the three types of operation, although the network composition was the same in both high and low demand, as the tasks being completed remained the same regardless of demand. Further illustration of the task network composition discussed is provided in Supplemental Materials (Figure 1). In all three scenarios, the subtasks (nodes) typically centre on the generation of a tactical picture, although the manner in which the picture is generated, differed between scenarios. In the DT scenario, tasks centred on knowledge of the priority contact that was required to be tracked, based upon the integration of information from sonar and periscope. Whereas in the INSO scenarios, task completion typically centred on the utilisation of visual information and sonar information, to best maximise submarine safety and covertness as the command team navigate inshore. The task network nodes and connectivity between nodes were verified by SMEs as being descriptive of how submarine command teams complete operations.

The first observation is that a number of tasks are identifiable as being at the level of the individual. A number of these tasks involve the basic acquisition and interpretation of data (i.e., the task detecting sonar contacts involves visually inspecting a difference in signal-to-noise ratio on the interface, and/or aurally confirming a mechanical noise at a particular bearing). An individual operator then transforms such assessment of data into internalised knowledge (i.e., another task involves the classification of sonar contacts, using narrowband sonar to assess frequency bands). This places context onto the data (i.e., bearing contact was aurally heard and type of noise) which is the process of converting data to information to at the level of the individual. These tasks can be viewed as collections of situation assessment processes, as individual operators, using a range of different sensors, build knowledge that is co-ordinated to inform team knowledge. A number of tasks are identifiable as representing the integration of knowledge at a team level. These tasks typically involve the integration of multiple individual tasks via data synthetisation. An example of this is the task node merging visual and sonar picture involved the synthesis of data and information generated at the level of the individual, by PERI and SOPs, to facilitate overall picture understanding, facilitated by SOCs and OPSO. The processes that guide the synthesis of data to generate a complete tactical picture involve problem detection and co-ordination by senior operators (e.g., OPSO and SOC) to allow the conversion of individual knowledge into team knowledge. The task networks are cyclical, to promoting an evolving tactical picture that can be adapted by the command team based upon environmental change (e.g., the refinement of tactical solutions). This is an example of adaption and re-planning being co-ordinated by OOW, OPSO, and SOC after inspection of the tactical picture. This exemplifies how team knowledge can be feedback to individual operators (e.g., the TMAs) to inform knowledge at the level of the individual, resulting in original solutions being correct/refined.

A second observation is that the relative importance of each subtask (node) varies depending between the different scenarios. This provides an indication of the task nodes that are most critically to the generation of team knowledge in particular operational contexts. For example, the sociometric status of tasks such as raise periscope (INSO = 0.23, DT = 0.13) and complete second periscope sweep (INSO = 0.20, DT = 0.09), was much greater within the INSO task network, compared to the DT task network. This indicated that during INSO, PERI is the most critical operator in terms of task completion to facilitate a situation assessment. The use of periscope is much more critical to safe submarine operation during INSO, highlighted by the importance of associated task nodes. However, during a DT the sociometric status of the task nodes detect sonar contacts (INSO = 0.16, DT = 0.25) are much higher than in the INSO operation. This indicates that during a DT operation the tasks completed by the SOPs are most critical for adequate situation assessment. This is due to the fact that the submarine is operating from deep (so periscope cannot be used) and the command team want to stay covert, making passive sonar the best sensor. Interestingly a number of task nodes such as designate sonar contact had similar sociometric status (INSO = 0.13, DT = 0.13), but differing centrality (*INSO* = 14.27, DT = 20.65) when comparing the INSO and DT task networks. This indicates that the importance of certain tasks remain critical, regardless of scenario but their relevance to particular operation types may vary.

The task nodes discussed above primarily relate to situation assessment at the level of the individual or in sub-teams (e.g., sonar room). However, a number of the task nodes directly represent the completion of macrocognitive processes, with different importance depending on scenario type. For example, the task node build sonar picture has higher sociometric status (INSO = 0.10, DT = 0.16) in the DT task network compared to INSO. The building of a sonar picture requires effective co-ordination and problem detection by SOC with the SOPs to ensure that all sonar sub-tasks (e.g., detection and designation) have been adequately completed. The sonar picture is critical during a DT scenario as this is the primary sensor used for situation assessment. Yet the sociometric status (INSO = 0.26, DT = 0.16) of the task node confirm tactical picture is much higher in the INSO task network compared to DT. Confirmation of the tactical picture requires adaption and re-planning by higher command. Enabling the making of tactical decisions such as the performing of maneuverers (i.e., perform ranging manoeuvre) to confirm the tactical picture generated from situation assessments, often from multiple sensors across time (e.g., visual and sonar merged). This requires effective co-ordination (e.g., merging information from differ sensors) and problem solving (i.e., refinement of incorrect solutions), to understand and correct issues with the tactical picture that could compromise safety (i.e., collision due to incorrect contact solution). Confirmation of the tactical picture has such high sociometric status during INSO as it is essential for ensuring submarine safety when navigating inshore as confirmation is critical to safety when operating at shallower depths during INSO.

**Table 2**

Mean (and standard deviation) task frequency count

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | RTPD |  | INSO |  | DT |  |
|  | Low | High | Low | High | Low | High |
| Detect Sonar  | 4.00 (1.89) | 8.70 (4.22) | 4.60 (1.35) | 7.80 (3.01) | 5.30 (2.0) | 13.20 (4.3) |
| Designate Sonar  | 3.30 (1.64) | 7.70 (4.85) | 3.40 (1.58) | 5.40 (2.32) | 4.70 (1.34) | 10.00 (3.53) |
| Classify Sonar  | 3.80 (1.87) | 10.50 (4.30) | 3.10 (2.18) | 6.10 (2.02) | 4.70 (1.57) | 8.60 (3.44) |
| Sonar Speed  | 5.40 (2.27) | 10.90 (5.60) | 4.40 (3.44) | 7.10 (3.21) | 6.30 (1.83) | 9.20 (3.12) |
| Sonar Course  | 1.20 (1.23) | 4.90 (2.13) | 1.70 (2.36) | 3.00 (3.65) | 1.90 (1.85) | 4.60 (3.72) |
| Sonar Merge | 3.40 (1.35) | 2.80 (1.81) | 0.30 (0.67) | 1.40 (1.07) | 2.50 (2.01) | 3.20 (1.69) |
| Sonar Solution | 4.60 (1.96) | 10.70 (3.53) | 2.80 (1.62) | 4.20 (2.25) | 5.40 (2.32) | 9.00 (2.87) |
| Refine Solution | 4.20 (3.58) | 5.10 (3.63) | 4.40 (1.96) | 5.50 (5.10) | 3.00 (1.49) | 5.70 (3.37) |
| Change Parameter | 4.40 (2.46) | 4.30 (2.06) | 7.30 (2.71) | 6.30 (0.95) | 5.90 (2.56) | 8.30 (2.98) |
| Raise Periscope | 1.00 (0.00) | 0.80 (0.42) | 2.80 (0.92) | 2.80 (1.03) | 1.40 (1.26) | 1.10 (0.32) |
| Complete Sweep | 1.80 (0.63) | 0.80 (0.42) | 4.30 (1.06) | 4.50 (1.35) | 2.50 (1.78) | 0.40 (0.70) |
| Detect Visual  | 1.70 (0.95) | 1.40 (1.07) | 5.10 (2.13) | 5.20 (1.87) | 3.50 (1.90) | 1.60 (1.07) |

*Note*. Pertinent differences and similarities in frequency of task completion due to scenario type and demand are highlighted in black

The frequency of task completion was statistically significantly affected by demand *F*(1, 189) = 118.99, *p* < .001, ηp2 = .39, scenario type *F*(2, 378) = 8.70, *p* < .001, ηp2 = .05, task type *F*(20, 189) = 37.89, *p* < .001, ηp2 = .80, and the interaction between task type and scenario *F*(40, 378) = 9.22, *p* < .001, ηp2 = .49. Overall significantly more tasks were completed in the high demand scenarios compared to low demand (see Table 2). In the high demand scenarios the command team had a greater volume of contacts to manage, therefore situation assessments required more detections, designations, and speed estimates to be completed. However, it appears that dedication of more resources to situation assessment came at a cost to the completion of additional macrocognitive processes in the high demand scenarios. For example, despite a much greater volume of contact detections and designations in the high demand scenarios, the number of solution refinements and sonar merges completed was similar in the high and low demand scenarios (particularly RTPD and DT). This may indicate that due to capacity limitations the command team could dedicate fewer resources to problem detection (i.e., refinements) and co-ordination (i.e., effective merges). However, this may simply reflect a different team strategy, as planning and adaption processes, enacted by higher command (e.g., OOW, OPSO, and SOC) resulted in identification of priority contacts (i.e., posing the biggest risk) that were co-ordinated to become the focus of situation assessment and problem detection (i.e., refinement of solutions). This still indicates that the command team was operating at maximum capacity during the high demand scenarios, resulting in task shedding. The frequency of task completion across the INSO scenarios revealed much smaller differences between high and low demand compared to differences observed during the DT and RTPD scenarios (see Table 2 – sonar detections and speed estimates). Interestingly the distribution of task completion was also more even across all task types, such as the detection of sonar, contacts, and the detection of visual contacts (see Table 2). This indicates that the INSO scenarios require much more team co-ordination to facilitate the building of a tactical picture from numerous sensors, whilst routinely completing manoeuvres (e.g., changing submarine parameters) to find the safest navigational path inshore.

Post hoc tests revealed differences in the frequency of task completion across the different scenario types. Again, it is clear that certain tasks are completed more frequently in particular scenarios. For example, the tasks raising periscope, complete visual sweeps, and detect visual contacts are completed significantly (*p* <.01) more frequently in the INSO scenarios than the DT, and RTPD scenarios. However, tasks such as detection and calculation of sonar speed estimates are completed significantly (*p* <.01) more frequently in the RTPD and DT scenarios. This again highlights that the sensors primarily used for situation assessment vary depending upon operational requirements, therefore co-ordination of command team activity and planning processes are being completed differently depending upon operational requirements. Ultimately, the tactical picture that informs tactical decision making by the OOW can be generated in a variety of ways, as the generation of team knowledge is not a consistent process. This is further emphasized by the fact that the task of changing submarine parameters such as course and speed, are completed significantly (*p* <.05) more frequently in the INSO and DT scenarios than the RTPD scenarios. The making of such decisions means that the submarine can adequately track a contact that may be attempting to avoid detection or avoid hazardous contacts whilst navigating inshore. The changing of submarine parameters is a tactical decision co-ordinated by the OOW (the only operator who communicates with SHC). In scenarios where such actions are completed more frequently, it is likely that adaptive planning will also need to occur more frequently, as every change to own submarine parameters is likely to effect the accuracy of the tactical picture generated prior to any manoeuvre being undertaken (e.g., contacts may be lost in sonar baffles). Understanding the frequency of task completion can provide insight into macrocognitive processes by highlighting how much adaption, planning, and co-ordination is required within the command team for such tasks to be undertaken.

**Discussion**

The current work provides a detailed description and direct comparison of three operational scenarios routinely completed by submarines. Understanding the functionality of sociotechnical systems is inherently difficult due to the complex nature of their composition (Shattuck & Miller, 2006; Stanton, 2014; Walker et al., 2009). The use of a simulated environment designed with SMEs (i.e., good fidelity) combined with standardised network metrics keep the research true to NDM principles (Klein, 2015) whilst attempting to formally quantify macrocognition (Thomson et al., 2015). The network analysis approach facilitated direct observation of cognition occurring between the heads from raw communication data to reveal emergent team processes (Cooke et al., 2010; Wildman et al., 2013). This included how situation assessments are completed using data from different sensors at the level of the individual and problem detection via co-ordination (Fiore et al., 2010). The capacity to measure macrocognition is critical for developing understanding of the processes involved and examination of interventions that may optimise command team performance (Wildman et al., 2013).

**Macrocognition in Submarine Command and Control**

An overview of the macrocognitive processes revealed by the EAST analysis is presented in Figure 3. The submarine control room is analogous to human working memory, acting as an interface between the environment, internal memory, and action (Baddeley, 2000; Radvansky, 2017). The completion of situation assessment requires the generation of knowledge from data at the level of the individual to inform awareness of surrounding contacts. Individual operators interact with interfaces presenting processed data from a particular modality, to complete this process. The operators primarily involved in situation assessments were the SOPs who are required to detect and designate contacts using sonar, SHC who monitors own submarine parameters, and PERI who is required to detect and designate contacts using periscope (Dominguez et al., 2006; Stanton & Roberts, 2017).



**Figure 3.** A schematic representation of the submarine control room with the macrocognitive processes revealed by the EAST method

The command team are also required to detect problems that might negatively impact making sense of the environment, such as checking that sonar and periscope designations are correct. This is completed via communication between operators completing the same tasks (e.g., SOPs and TMAs) and operators responsible for moderating individual knowledge generation. A limiting factor of team performance is how effectively such communication occurs (Carletta et al., 2000; Driskell et al., 2017; Salas et al., 2001). Co-ordination processes facilitate synthesis of information from multiple sensors; this primarily requires information exchange between OPSO and SOC. These operators exchange relevant sensory knowledge including contact speed, and course estimates. Effective co-ordination of individual knowledge from different modalities creates knowledge at the level of the team, represented as a tactical picture on the OOW interface (Hicks et al., 2001). The tactical picture is used to inform re-planning or implementation of adaptive tactics to achieve mission objectives. Tactical decisions are made by the OOW but are informed by interpretation of the tactical picture informed by the command team (Dominguez et al., 2006).

**Applications**

A number of significant differences were observed when comparing RTPD, INSO, and, DT scenarios. These differences reveal how macrocognitive processes are impacted by different operational requirements and contextual demand (Bateman, 2011; Duryea et al., 2008; Keyton & Beck, 2010). The configuration of control rooms and command team structure has the potential to optimise macrocognitive processes. For example, the structure of the social networks remained stable across scenarios, potentially resulting from physical limitations and/or team structure (Stanton et al, 2010). Despite this, the contributions of operators in the network and strengths of connections between nodes varied between scenarios, revealing differences in macrocognitive processes (e.g., top down vs. bottom up tactical picture generation). The design of flexible control rooms that facilitate macrocognitive processes may optimise team performance across many domains (Roco & Bainbridge 2003; Santos et al., 2008; Showalter, 2005).

The OOW communicated more frequently with SHC during INSO and, DT when manoeuvring the submarine is paramount to safety and mission objectives (Dominguez et al., 2006; Duryea et al., 2008). Highlighting that the OOW will communicate with anyone in the command team they require information from to confirm the tactical picture or enact tactical decisions (Dominguez et al., 2006). Placing the OOW in the centre of the control room may help to co-ordinate processes such as adaption, planning, and tactical decision-making. The information element visual had higher sociometric status in the INSO scenarios. When completing INSO the waters are typically shallow, meaning submarines operate where the potential for collisions with surface vessels is greater (Duryea et al., 2008; Glosny, 2004). It may be useful during an INSO to place PERI in the centre of the control room with OOW, as this is the primary sensor used to inform a situation assessment. However, during a DT operation the sociometric status of SOC is at its highest, indicating that this operator should be positioned in the centre of the command team with OOW. In general, the load placed on OPSO and SOC (i.e., high sociometric status) is very high. This seems to be the result of these operators being required to actively engage in problem detection and co-ordination of information from different modalities. A solution may be to co-locate operators who are dependent on each other for information (e.g., SOPs and TMAs) to reduce the load on co-ordinating operators acting as information brokers (e.g., OPSO and SOC).

**Conclusions**

The EAST method is offered as one way of modelling macrocognitive processes in teams, based on the communications between operator’s methods (Cooke et al., 2013). Social network analysis metrics can help to quantify such processes and afford empirical investigation (Wildman et al., 2013). The use of novice participants facilitated the recruitment of a large sample size, producing a body of work with good statistical power. However, the use of novice participants with short training histories is also a limitation of the current work, questioning its generalisability. The use of novice participants for command and control studies has been shown to be effective in previous research (Walker et al., 2010). Moreover, 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, see Stanton, 2014; Stanton & Roberts, 2017). Despite this, future research should aim to compare navy teams to non-navy teams to ascertain the validity of the work, in keeping with the origins of NDM research (Klein, 2015). Future work should also examine the potential for more flexible command teams in terms of control room configuration, team structure (e.g., hierarchy), and information communication within the command team (e.g., policy) so that they can be adapted to the type of operation being undertaken (Driskell et al., 2017).

**Author contributions**

**Dr Aaron P J Roberts** ran the experimental studies, analysed the data and co-authored the manuscript. **Professor Neville A Stanton** was the Principal Investigator on this project. He managed the research, supervised the analysis and co-authored the manuscript.

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