The effects of team co-location and reduced crewing on team communication characteristics

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**Abstract**

The manner in which control rooms are configured can impact the flow of information between command teams. Previous research revealed bottlenecks of communications between the Sonar Controller (SOC) and the Operations Officer (OPSO) in submarine control rooms. One way to relieve such bottlenecks is to co-locate operators reliant on one another for task relevant information. The aim of the current studies was to use multiple command teams to empirically examine a novel submarine control room configuration and a reduced crew size in comparison to a baseline of contemporary operations to see if such bottlenecks could be removed. Ten teams performed high and low demand Dived Tracking (DT) scenarios in a simulated submarine control room. Activities and communications of the teams were recorded and quantified using the Event Analysis of Systemic Teamwork (EAST) method affording statistical comparisons with a baseline condition of contemporary operations. The findings showed that the co-location of operators relieved the bottleneck of communications between the SOC and the OPSO. Although overall communications increased, this was more balanced across the team and was more adaptive to scenario demand. This was coupled with a significant increase in task completion, even with a reduced crew size, suggesting greater efficiency and productivity. Future research should seek to validate the changes observed with objective measures of task performance.

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

**Introduction**

**Distributed cognition**

A primary benefit of team environments is the affordance of multiple skills, training and experience that individuals alone would not possess (Alnuaimi, Robert, & Maruping, 2010). In a submarine control room, multiple operators are trained to complete specific tasks such as sonar data processing and target motion analysis to develop a tactical picture in support of mission objectives (Stanton, 2014; Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015; Loft, Sadler, Braithwaite, & Huf, 2015; Stanton & Roberts, 2017). The tactical picture is utilised by the Officer of the Watch (OOW) to support decision making. The effective generation of a tactical picture relies on multiple command team members integrating information from disparate sources (i.e. senor types) to build awareness of the external environment (Dominguez, Long, Miller, & Wiggins, 2006). In such contexts, cognition is not solely in the mind of an individual but is distributed across many individuals who are part of the team (Walker, Stanton, Salmon, & Jenkins, 2009). This occurs in many domains; with multiple operators often working in smaller clusters, creating a system of systems (Harris & Stanton, 2010). Examples include the interactions between pilots and air traffic controllers in aviation (Walker, Stanton, Baber, Wells, Gibson, Salmon, & Jenkins, 2010), the relationship between surgeons, anaesthetists and nurses in health care (Hazlehurst, McMullen, & Gorman, 2007) and the co-ordination between different control rooms in energy distribution (Salmon, Stanton, Walker, Jenkins, Baber, & McMaster, 2008).

A critical challenge is the effective sharing of information between individual operators, to create knowledge at the level of the team in support of collaborative goals (Fiore, Smith-Jentsch, Salas, Warner, & Letsky, 2010). In complex environments with multiple operators, it is important to examine ‘cognition in the head’ of operators and ‘cognition between the heads’ at the level of the team. The processes which support coping with real-world complexity at the individual and collective level are known as macrocognition (Klein, Moon, & Hoffman, 2006; Cooke, Gorman, & Kiekel, 2008). Team based processes are typically facilitated by supporting technologies that enable adequate interdependence between operators (Stanton, Salmon, Walker, & Jenkins 2009; Zhang & Patel, 2006). It is important to adopt a sociotechnical systems approach to the design, development and evaluation of control rooms and technologies (e.g. interfaces) within them across many domains (Stanton, 2011, 2014; Salas, Burke, & Samman, 2001; Lee & Kantowitz 2005). Furthermore, the optimal engineering of complex sociotechnical systems requires assessment of macrocognition as it naturally occurs in complex decision-making environments (Klein, Ross, Moon, Klein, Hoffman & Hollnagel, 2003). The examination of verbal communications between team members has been demonstrated to be an effective way of measuring performance from a macrocognitive perspective at the level of the team (Roberts & Stanton, 2018). The Event Analysis of Teamwork (EAST: Stanton, Baber, & Harris, 2008) adopts a network approach to examine communications between agents in a system. The social network approach has great potential as a tool for measuring team cognition (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 (Roberts & Stanton, 2018). 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). A benefit of the network analysis approach to information is that it enables the calculation of network metrics (e.g. emissions, receptions and sociometric status) that quantify the social, information, and task network composition between scenario types and levels of demand. This affords empirical investigation of how independent variables (e.g. demand and system design) impact network metrics providing insights at the level of the team. This is a key requirement for the advancement of macrocognition theory (Letsky & Warner, 2008; Thomson et al., 2015).

**Submarine control room design**

A previous study conducted by Roberts, Stanton, and Fay (2018) empirically examined the current ways of working of submarine command teams when completing a Dived Tracking (DT) operation. This highlighted a number of ways in which control room design could be improved. The first observation was that the submarine command teams coped with increased demand by communicating more frequently, exchanging a greater range of information, that was less structured temporally and in terms of composition (Roberts et al., 2018; Stanton & Roberts, 2017). The number of communications that can occur between operators is finite due to basic perceptual limitations (Roberts & Cole, 2018; Baddeley, 2000). However, communication is critical for the attainment of shared team awareness, such a process can be the determining factor in terms of team workload rather than the task work itself (Salas et al., 2001; Stanton, 2011; Carletta, Anderson, & McEwan, 2000). The configuration of a team and how technology supports communication can greatly impact the effectiveness of overall team performance (Stanton, Rothrock, Harvey & Sorensen, 2015; Espevik, Johnsen, Eid, & Thayer, 2006).

In a submarine control room the sonar operators (SOPs) analyse sonar data providing information (e.g. bearing and speed estimates of contacts) that the Target Motion Analysis operators (TMAs) require to effectively calculate solutions concerning contact behaviour of contacts. During a DT operation, the submarine is operating at depth, typically relying on passive sonar from multiple arrays, to generate a tactical picture safely but also covertly (Bateman, 2011; Zarnich, 1999; Glosny, 2004; Duryea, Lindstrom, & Sayegh, 2008). In current control room configurations, the SOPs are located in a separate room from the TMAs, despite being highly dependent on each other for information (Stanton, 2014; Loft et al., 2015; Loft et al., 2015; Stanton & Roberts, 2017). In the baseline studies an information bottleneck was observed between the Sonar Controller (SOC) and the Operations Officer (OPSO) in the command team. There is a reliance on these operators to act as information brokers between multiple SOPS and TMAs (Stanton et al., 2018; Stanton & Roberts, 2017; Roberts & Stanton, 2018). The current configuration is due to historical engineering limitations, such as the requirement for a quiet workspace when processing aural data. Advancements in engineering mean that such issues can now be overcome, such as with the utilisation of noise cancelling headphones for periods where ambient noise needs to be supressed (Arrabito, Cooke, & McFadden, 2005). Despite this, the configuration and location of submarine control rooms has remained relatively consistent across a century of operations, at least in the UK (Stanton, 2014). The co-location of operators dependent on each other for information (e.g., SOPs and TMAs) has the potential to reduce the load placed on OPSO and SOC as information brokers, simultaneously removing this bottleneck of information transition (Roberts et al., 2018; Roberts & Stanton 2018). A critical issue remains that the SOPs and TMAs are required to pass information through their superiors to facilitate additional processes (e.g., quality checking and co-ordination) supporting team cognition (Roberts & Stanton, 2018). It is important to consider how changes to configuration might impact macrocognitive processes, and, ultimately team performance in complex sociotechnical control room environments (Klein et al., 2003; Roberts & Stanton, 2018). It is acknowledged that some of the roles and shortfalls discussed are specific to UK platforms. However, as the pace of technological advancement continues to increase, the requirement to optimise the design of sociotechnical systems is a challenge facing many countries across many domains.

**Production Blocking**

Production blocking occurs in oral communication because only one person can speak at a time. This is particularly prevalent when teams are using verbal electronic text mediums where the software only permits synchronous communication, i.e. limits communication to one speaker at a time (Stanton, Ashleigh, Roberts & Xu, 2003). This has the potential to lead to erroneous, simplified or reduced occurrence of critical verbal information transition due to the limited nature of human phonological working memory stores (Roberts & Cole, 2018). It is a critical issue in technology supported and location distributed teams, with tools such as automation frequently increasing the complacency and decision bias of operators across many domains, potentially due to ineffective system design (Simms & Nichols, 2014; Ashleigh, Roberts & Xu, 2003; Parasuraman & Manzey, 2010). Production blocking has been demonstrated to account for a loss of productivity within groups engaged in real world brainstorming activities (Diehl & Stroebe, 1987). The mechanisms that cause such interference are related to unpredictable temporal lags with regard to information transition which disrupt the organisation and flexibility of idea generation in group contexts (Nijstad, Stroebe & Lodewijkx, 2003). In current control room configurations, there is role duplication (e.g., multiple SOPs and TMAs), a reduction in supervisory control (e.g., OOW coverage of multiple rooms) and high task difficulty when working with ambiguous information (Kirschenbaum, 2001). It appears that the conditions for production blocking are met, reinforced by the observation that one TMA and SOP is typically involved to a lesser extent (i.e. blocked) in information transition (Roberts et al., 2018; Roberts & Stanton, 2018). In such instances, members of the command team had to wait extended (and unpredictable) periods before information could be passed. A persistent effect of continued production blocking, where verbal communication is limited (i.e. only one person can talk at a given time) is the inadvertent suppression of ideas, distraction and/or forgetfulness, contributing to reductions in overall productivity (Diehl & Stroebe, 1987; Stanton et al., 2003; Simms & Nichols, 2014).

It is suggested that the design of sociotechnical systems can engineer conditions where production blocking can occur (Watkins, Mukherjee, Onder, & Mattila, 2009; Stanton, Ashleigh, Roberts & Xu, 2003). For example, in submarine control rooms, two SOPs are required to pass all information to wider members of the command team through a single operator (SOC). This operator has additional co-ordination duties that limit their availability to relay information from SOPs (Roberts & Stanton, 2018). In many domains operational economic costs have been minimized by reducing crew size (Walters, French, & Barnes, 2000; Stanton, Harris, & Starr, 2016; Salotti, Heidmann, & Suhir, 2014). The economic savings associated with reduced crew sizes can be substantial (Allender, 2000) and in certain situations can improve efficiency, based upon minimising production blocking (Watkins, Mukherjee, Onder, & Mattila, 2009). However, a primary consideration is the impact a reduction in crew size has upon team performance and operational safety (Salotti, Heidmann, & Suhir, 2014). Ultimately, the productivity of larger command teams will be limited, unless control rooms are designed to maximise the flow of information between operator’s co-dependent on information for task completion (Stanton, Roberts & Fay, 2018). An investigation of crew size, therefore, is not necessarily concerned with a manning reduction, but whether command team capacity is being optimally utilised. Recent work has investigated how a co-located control room configuration and a reduction in crew size impact verbal information transition and productivity (Stanton, & Roberts, 2019). The novel configuration had a positive impact on information flow and overall productivity, however such work was focused on a particular operation – a return to periscope depth. The current work seeks to extend such understanding to broader operational objectives, in particular the dived tracking of contacts.

In the current work, a novel co-location control room configuration was directly compared to a baseline comparator reported previously (see Roberts, Stanton & Fay, 2018). The primary aim of the work was to assess if the novel configuration optimised verbal information transition and productivity, which is critical for cognition at the level of the team. A secondary aim was to examine if such benefits afforded the removal of two operators from the command team. To achieve this two experiments were conducted. Firstly, the novel configuration was compared to baseline with the same command team size (as baseline) and secondly with a reduced command team size. The inherent complexity of sociotechnical systems makes precise predictions difficult. In particular, it is unclear how this may impact the structure of information transition (e.g. information networks) or overall productivity (e.g. frequency of task completion). Despite this, a number of hypotheses were tentatively proposed:

1. (a) The co-location configuration will alter the distribution of verbal communication between operators leading to changes to the composition of the social networks with regard to emissions, receptions, sociometric status and centrality in comparison to baseline. In particular, emissions and receptions between SOPs and TMAs will increase, whilst emissions and receptions between the SOC and OPSO will decrease.

(b) The distribution of communications will also be altered when two operators are removed from the co-location configuration, the volume of verbal communications will be reduced with fewer emissions and receptions in comparison to baseline. However, emissions and receptions from the remaining SOP and TMA will increase in comparison to baseline.

1. (a) The co-location configuration will not change what information is critical to command team performance, therefore no significant changes to the composition of the information networks with regard to emissions, receptions, sociometric status and centrality will be observed in comparison to baseline.

(b) The total emissions and receptions contained within the information networks will decrease when two operators are removed from the co-location configuration in comparison to baseline.

1. (a) The co-location configuration will increase the volume of tasks completed by the command teams compared to baseline.

(b) The removal of two operators will reduce the volume of tasks completed by the command team compared to baseline.

1. (a) The workload of operators will reduce in the co-location configuration when compared to baseline.

(b) The workload of operators will increase with two operators removed compared to baseline.

**Method**

In the current study two experiments were conducted, firstly a novel co-location configuration and secondly the same configuration with a reduced crew size. The results of both experiments were directly compared to a baseline study previously conducted, which examined a contemporary control room configuration (Roberts, Stanton, & Fay, 2018). All baseline results have been reported previously, a limited amount are repeated in the current work for the purposes of comparison. The methods used across both experiments were almost identical, critical differences are highlighted below.

**Participants**

A total of 10 teams of 7 individuals (70 participants in total) were recruited opportunistically using posters and presentations at military Human Factors conferences. In the first experiment (co-location), a total of 59 males and 11 females participated with an age range of 20-48 (Mean= 28.94, SD= 7.02). In the second experiment (reduced crew) two operator roles were removed from the command team. This led to the removal of two participants from each team for the second experiment, which left a total of 44 males and six females remaining with an age range of 20-48 (Mean= 28.98, SD= 7.28). One of the teams were submariners from the British Royal Navy (RN). The study protocol received ethical approval from the University of Southampton Research Ethics Committee (Protocol No: 10099) and MoDREC (Protocol No: 551/MODREC/14).

**Equipment - The Submarine control room simulator**

A submarine control room simulator with nine networked workstations was built to be representative of a currently operational RN submarine. The simulator design and build was informed by Subject Matter Experts (SMEs) from the RN and relevant industry partners involved with the design and construction of UK submarines. The simulator was required to have adequate physical fidelity (e.g. realistic looking consoles and spatial constraints) to immerse novice participants but also have adequate task fidelity (i.e. realistic sonar models and interfaces comparable to operational environment) for expert teams to be engaged. A full description of the simulator build and validation process with regard to physical and task fidelity has been presented previously (see Roberts et al., 2015). The same DT scenarios used in baseline and the current experiments were developed with input from SMEs to be representative of real world DT operations. Scenario demand was manipulated by area of operation, contact behaviour (e.g. speed and course changes vs. steady) and the number of contacts detectable in the scenario (see table 1 for full description). The movements of contacts was predetermined to be consistent across all teams and each scenario lasted approximately 45 minutes. The scenarios have also been completed in the simulator by an expert submariner cohort (Stanton & Roberts, 2017), with the observed effects being similar in direction to novices (Roberts & Stanton, 2018), providing assurances concerning the relative validity of the work.

Table 1. *Description of scenarios*

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Demand | No. Contacts | Description |
| Dived Tracking (DT) | Low | 3 – Fishing  1 – Sailboat  1 – Nimitz | Starting at periscope depth, locate and track priority contact (Nimitz warship) in nearby waters, scenario complete when all contacts held have been ranged and priority is tracked. |
| High | 7 – Fishing  2 – Merchant  1 – Nimitz | Locate and track priority contact (Nimitz warship) in nearby waters, after near Collison forces emergency go deep procedure. |

The control room included an Officer of the Watch station (OOW), an Operations Officer station (OPSO), a Sonar Controller station (SOC), two Target Motion Analysis stations (TMA), two Sonar Operator stations (SOP), a Ship Control station (SHC) and a Periscope station (PERI). The workstations ran the simulation engine Dangerous Waters (DW), a software package developed by Sonalysts, which featured networked workstations for each of the roles. In all conditions, participants communicated using headsets with push-to-talk functionality and a communication network with multiple channels any operator could enter (sonar, TMA, command, periscope and ship control). Participants could only monitor and/or communicate on one channel at any given time. In the co-location configuration, an additional channel (sonar/TMA) was added to the network. Participants were trained in military verbal protocol and instructed that all communications had to be completed via the headsets. Participants were instructed that information should be quality checked via senior operators (OPSO and SOC). However, all operators had the capacity to communicate with each other across all conditions. It should be noted that the role of the OOW was assumed by the same experimenter across all scenarios (including baseline). This was recommended by SMEs from the RN, as training the tactical understanding required for this role was not deemed to be achievable in a day. It was also proposed by SMEs that the role of SHC was outside the scope of the tactical aspects of the command team but was still required for adequate simulation fidelity. Therefore, this role was also completed by an experimenter to reduce recruitment requirements. This left 7 workstations which were randomly allocated to participants, these workstations deemed critical to the generation of a tactical picture. A comprehensive recording suite (e.g. web cameras and ambient microphones) allowed for the recording of all communications that occurred between operators.

**Design**

In the first experiment to examine the impact of the co-location configuration a 2 x 2 x 9 mixed design was used. The independent variables were configuration type (between subjects) scenario demand (within subjects) and operator role (between subjects). In the second experiment to examine the impact of co-location with reduced crew size a 2 x 2 x 7 mixed design was used. The independent variables were the same in both experiments except two operator roles were removed from the command team in the second experiment.

**The Co-location configuration**

The design and build of the co-location configuration was informed by evaluation of the results from the baseline studies by a panel of SMEs including RN submariners, industry partners involved with the design and construction of British submarine control rooms and Human Factors practitioners. The aim was to use an evidence-based, data-driven approach to design a submarine control room that reduced potential shortfalls identified during the baseline studies (Roberts, Stanton, & Fay, 2018). The primary changes that were agreed upon, along with rationales, are presented in table 2 and figure 1. In summary, the collapsing of the sound room and control room (baseline configuration) into a single space afforded the OOW greater coverage of the entire command team. It also facilitated the co-location of operators who were dependent upon each other for task relevant information. This included the SOC and OPSO, who communicated frequently during baseline creating a bottleneck of information flow. It also included the SOPs and TMAs who, in the baseline configuration were the most distant in terms of physical proximity but more critically in terms of social network distance.

Table 2. Overview of shortfalls revealed from baseline testing and recommendations from SME panel

|  |  |  |
| --- | --- | --- |
|  | Shortfall | Recommendation |
| 1 | A bottleneck in information flow between SOC and OPSO. This blocked production between the SOPs and TMAs. This was due to communication networks being monopolised by higher command and a requirement to ensure that command quality checked information passed between operators. | Position OPSO and SOC next to each other with visibility of each other’s screens. This facilitated monitoring of information exchange, with verbal intervention only when required. A sound/TMA network was also created to facilitate communication between SOPs and TMAs that could be monitored by senior operators where appropriate. |
| 2 | The large number of screens (in different rooms) OOW needs to observe. This led to production blocking as the OOW was required to verbally pull information. Communicating frequently across multiple network channels rather than monitoring | Position OOW in a location where they can view the work being completed by all operators. This facilitated the OOW monitoring communications channels rather than verbally communicating. |
| 3 | TMA reliance on information from SOPs to generate solutions (informing tactical picture). | Position TMA and SOPs next to each other so they can directly share information and view each other’s screens. Creation of an additional sonar/TMA communications channel to facilitate communication between these operators |
| 4 | A lack of shared awareness by the command team, particularly between the sound room and picture room. | Remove the separate rooms for the SOPs and TMAs creating an open workspace for all operators with more shared awareness of information and tasks. |



Figure 1. *Control room configurations.* Figure 1a is the baseline configuration. The shortfalls identified by baseline findings and SME recommendations included: **1.** A bottleneck in communications between OPSO and SOC, **2.** OOW being required to supervise two separate rooms, 3. TMAs and SOPs being highly reliant on each other for task relevant information but being distant (in terms of network composition and physical location) and **4.** A potential loss of shared awareness between the sound room and control room.

**Reduced crew size**

In the second experiment the same (co-location) configuration from experiment 1 was used, however, two operators were removed from the command team. It was decided to remove the roles of SOP2 and TMA2 from the command team (see figure 1). The decision to remove two operators, and which operators to remove was also informed by the SME panel. The baseline studies revealed that the pairs of SOPs and TMAs completed many similar tasks. Therefore, removal of one of these operators would not reduce command team functionality but would reduce capacity. The aim of the second study was to examine if a co-location configuration enabled the command team to cope with the removal of two operators when compared to baseline. Therefore, the selection of a TMA and SOP to be removed from the command team was not due to role redundancy, it offered the only feasible opportunity to reduce command team capacity without reducing functionality or changing additional aspects (e.g. interfaces, task allocation).

**Measures**

A shortened version of Event Analysis for Systemic Teamwork (EAST: Stanton, Baber, & Harris, 2008) method was used to examine the macrocogntion of the command teams. This method has been presented in a previous study to model submarine command and control (Stanton, 2014) and has also been applied in other domains such as emergency services (Houghton, Baber, McMaster, Stanton, Salmon, Stewart, & Walker, 2006), road safety (Salmon, Lenne, Walker, Stanton, & Filtness, 2014), air traffic control (Walker, Stanton, Baber, Wells, Gibson, Salmon, & Jenkins, 2010) aviation (Stewart, Stanton, Harris, Baber, Salmon, Mock, & Kay, 2008) and military risk assessment (Stanton & Harvey, 2016). EAST examines complex sociotechnical systems using a network approach. Social networks examine the verbal communications between operators in the command team; 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.

Table 3. *Definitions of global network metrics and nodal metrics*

|  |  |
| --- | --- |
| Metric | Definition |
| Global |  |
| Nodes | Entities in a network (people, information or tasks for the purposes of this paper) |
| Edges | 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 number of possible connections |
| Nodal |  |
| Emission | Number of links emanating from node in the network |
| Reception | Number of links going to each node in the network |
| Sociometric | Number of emissions and receptions relative to the number of nodes in the network |
| Centrality | Extent to which network revolves around a single node |

The construction of networks requires the generation of static adjacency matrices derived from the communications that took place between operators within the command team. To generate the social networks, all audio recordings were transcribed and a frequency count of communications between operators was compiled in adjacency matrices for each team across each scenario. The nodes in the information networks were determined using Leximancer software (version 2.1) a software program that automatically identifies concepts, or themes in text documents. One function of Leximancer is the generation of adjacency matrices detailing the relatedness of information within a text document. 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 SMEs before frequency counts of all tasks were completed.

The social, information and task networks were generated using AGNA software (version 2.1.1) a network analysis software program. A number of network matrices can be calculated to facilitate understanding of network composition in terms of overall structure (global metrics) and the individual nodes contained in the network (nodal metrics). Definitions of all metrics are provided in table 3. If a social network contains lots of edges, it means that many operators are communicating directly (i.e. not via additional command team members). If such a network also has high cohesion then most of these communications are bi-directional. This may indicate that information is being requested and received, rather than orders being provided in a top down fashion. Furthermore, if information such as bearing has high sociometric status then this node is very critical to the overall structure of the network as it is highly connected to all other nodes with regard to emissions (i.e. how often bearing leads to another information element) and receptions (i.e. how often another information element leads to bearing). If the centrality of bearing, as a node in the network was also high, it would indicate that a vast amount of all other information nodes in the network are connected to bearing.

To examine the subjective spare capacity of operators the Bedford workload scale (Roscoe, & Ellis, 1990) was used. The Bedford scale is unidimensional; it required operators to rank whether the workload was tolerable (1-10, low to high) for the task and if workload was satisfactory without reduction, using a flow diagram tool (Roscoe, & Ellis, 1990). The National Aeronautical Space Administration Task Load Index (NASA TLX) was used to examine the perceived workload and performance of operators (Hart & Staveland, 1988). The NASATLX required operators to rate workload on six scales (1-20, low to high - mental demand, physical demand, temporal demand, performance, effort and frustration) via questionnaire (Hart & Staveland, 1988).

**Procedure**

Identical procedures were used for the baseline, co-location and reduced crew size conditions. The training and testing protocol also remained identical (see Roberts, Stanton & Fay, 2018 for a full description). Participants attended the submarine simulator for two/three full days from 8am – 5pm. On the first day informed consent was obtained from participants and a simulator induction was completed, before team roles were randomly assigned. Participants spent the morning of the first day (training) watching a set of general submarine control room operation tutorials, whilst the afternoon was spent watching workstation specific tutorials and practicing tasks individually before practicing as a functional command team. Each tutorial lasted approximately 45 minutes with regular breaks and refreshments provided between tutorials. Participants were encouraged to ask questions about the operation of their workstations and their tasks, as well as the communications protocol.

The second day (testing) started with a refresher training scenario as a functional command team. This was monitored by experimenters to check that all tasks were being accomplished correctly in line with set criteria provided by SMEs (e.g. adequately detecting surrounding vessels, gaining solutions concerning surrounding vessels and steering the submarine safely to relevant courses and depths). Following this the first scenario began – all recording devices were started, and a verbal time stamp was read aloud for synchronization purposes. Each scenario started with an OOW briefing outlining the mission objectives (see table 1). When the mission objective had been achieved the end of the scenario was called. At this point participants completed the NASA TLX and Bedford scales (presentation order was counterbalanced). Participants were then provided with a short break before the start of the next scenario. Each team completed both scenarios, and participants occupied the same positions in the command team. To reduce order effects scenario presentation was counterbalanced across all teams. A third day of testing was also completed by participants who were required for both the co-location configuration and the reduced crew size condition. The order of testing was counterbalanced to prevent practice effects (i.e. co-location and reduced crew size testing days were reversed). At the end of the final scenario participants were provided with a full debrief and thanked for participating.

**Analysis of data**

In experiment 1, to examine the effect of configuration and scenario demand on global network metrics a 2 x 2 (manipulation x demand) mixed ANOVA was conducted. A 2 x 2 x 9 (configuration x demand x operators) mixed ANOVA was conducted to examine the effect of configuration, scenario demand and operator role on social node metrics. To examine the effect of configuration and scenario demand on information node metrics a 2 x 2 x 14 (manipulation x demand x information nodes) mixed ANOVA was conducted. 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. A 2 x 2 x 12 (manipulation x demand x task nodes) mixed ANOVA was conducted to examine differences in the frequency of task completion based upon configuration and demand. The task nodes were derived by watching the videos and listening to audio to ascertain when a particular task was performed. The task networks were verified by SMEs before frequency counts were completed. The 17 nodes included in the statistical analysis represented tasks for which frequency counts could be conducted, with similar tasks being clustered together (i.e. detect sonar contacts corresponds to hull and bow array). In experiment 2, the statistical analysis conducted from the reduced crew size (study 2) was almost identical, except a 2 x 2 x 7 (configuration x demand x operators) mixed ANOVA was conducted to examine individual social nodes between baseline and the reduced crew size. All significant main effects were examined further by conducting post hoc pairwise comparisons. The Bonferroni correction method was used (α = 0.05/number of comparisons indicates statistically significant result) to account for multiple comparisons. Statistical analysis was conducted using IBM SPSS v21.

**Results**

**Hypothesis 1a:** The co-location configuration will alter the composition of the social networks

The cohesion (*F*1, 18 = 22.72, *p* < .01, ήp2 = .56) of the entire networks was statistically significantly affected by configuration type. The cohesion of the networks was statistically significantly higher in the co-location configuration. This indicates that a greater number of operators in the command team were communicating with each other. Moreover, more of these communications were reciprocal, indicating that requests for information were being answered more directly between operators (i.e. one-to-one) than in the baseline configuration (see table 4 and figure 2). The interaction of configuration type and role statistically significantly affected the total emissions (*F*8, 162 = 6.40, *p* < .01, ήp2 = .24) and receptions (*F*8, 162 = 4.57, *p* < .05, ήp2 = .18) of operators. This indicates that the co-location configuration impacted different members of the command team differentially in terms of passing and receiving verbal information. Post hoc analysis revealed SOC and PERI had statistically significantly fewer emissions in the co-location configuration than baseline, although only SOCs total receptions reduced. TMA1 and TMA2 had statistically significantly more emissions and receptions in the co-location configuration compared to baseline. This reveals that more information was being communicated and received by the TMA operators (see table 5 and figure 2). However, less information was being communicated and received by SOC suggesting this operator was acting less as an information broker in the co-location configuration. The volume of communications between the SOPs and TMAs increased in the co-location compared to baseline, whilst the volume of communications between OPSO and SOC decreased (see figure 2). The fact that PERI was receiving the same amount of information but communicating less may suggest that information was being passed more efficiently (e.g. fewer repeat requests) as during a DT operation PERI should be a passive information receiver for large parts, in preparation for a potential reduction in depth when periscope might be used. The number of communications completed by all other members of the command team were not significantly different to what was observed in the baseline configuration. Indicating that the structure of communications has changed but some consistency has remained.

Table 4. *Means and standard deviations of global social network metrics for baseline, co-location and reduced crew size*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | | | |  |  | Effect of  Co-location | Effect of Crew Size |
|  | Baseline | | Co-location | | Reduced Crew | |  |  |
|  | Low | High | Low | High | Low | High |  |  |
| Edges | 32.00 ± 3.37 | 32.66 ± 2.11 | 33.70 ± 2.79 | 32.50 ± 3.60 | 21.70 ± 1.42 | 19.90 ± 2.28 | .46 | 205.46\*\*\* |
| Density | 0.44 ± 0.05 | 0.45 ± 0.03 | 0.47 ± 0.04 | 0.45 ± 0.05 | 0.52 ± 0.03 | 0.48 ± 0.05 | .51 | 10.64\*\*\* |
| Cohesion | 0.32 ± 0.02 | 0.34 ± 0.05 | 0.40 ± 0.05 | 0.38 ± 0.05 | 0.47 ± 0.04 | 0.42 ± 0.06 | 22.72\*\*\* | 64.35\*\*\* |
| Total Interactions | 634.90 ± 142.64 | 787.78 ± 106.92 | 548.70 ± 100.78 | 817.10 ± 78.69 | 487.50 ± 59.99 | 697.50 ± 74.20 | .42 | 9.83\*\*\* |

\* p<.05, \*\*p<.01, \*\*\*p<.001, ± indication of plus or minus quantity

The interaction of configuration type and role statistically significantly affected sociometric status (*F*8, 162 = 5.68, *p* < .01, ήp2 = .22) and centrality of operators. The centrality of operators were statistically significantly affected by the interaction of configuration type, role and demand (*F*8, 162, = 2.89, *p* <.05, ήp2 = .13). Post hoc analysis revealed SOC had statistically significantly lower sociometric status in the co-location configuration than in the baseline condition (see table 5 and figure 2). Whereas the TMA operators had statistically significantly higher sociometric status in the co-location configuration compared to baseline. This indicates that the reliance on SOC as a critical information broker had been distributed across the command team with the importance of the TMAs as information brokers increasing. Furthermore, OPSO, SOC, PERI and SHC had statistically significantly lower centrality in the co-location configuration than in baseline. Whereas the TMAs and SOPs had statistically significantly higher centrality in the co-location configuration compared to baseline. This indicates that the SOPs and TMAs assumed more responsibility for the transition of information across the control room, reducing this load on OPSO and SOC. Interestingly, OOW had statistically significantly higher centrality in the co-location configuration high demand scenarios than in baseline high demand scenarios and SOC had statistically significantly lower centrality in the co-location configuration low demand scenarios than the baseline low demand scenarios. This indicates that the co-location configuration led to greater flexibility with regard to the operators responsible for the distribution of information. In the low demand scenarios OOW and SOC assumed less responsibility with regard to the distribution of information but in the high demand scenarios these operators were more involved or at least had maintained levels of information distribution when compared to baseline.

Table 5. Means and standard deviations of individual node social network metrics for baseline, co-location and reduced crew size

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Baseline | | | Co-location | | Reduced | | Baseline | | | Co-location | | | Reduced | |
|  | **Emission** | | |  | |  | | **Reception** | | |  | | |  | |
|  | Low | | High | Low | High | Low | High | Low | High | | Low | | High | Low | High |
| OOW | 94.4 ± 14.65 | | 114.89 ± 18.52 | 99.1 ± 25.61 | 130.4 ± 15.54 | 106.9 ± 25.4 | 135.5 ± 16.8 | 88.5 ± 19.45 | 108.22 ± 22.77 | | 73.3 ± 15.65 | | 103.1 ± 14.76 | 90 ± 21.38 | 112.4 ± 11.23 |
| OPSO | 166.5 ± 31.16 | | 199.11 ± 20.55 | 141 ± 30.24 | 208.9 ± 34.56 | 129.9 ± 18.2 | 186.3 ± 29.49 | 158.5 ± 29.38 | 203 ± 18.68 | | 136.8 ± 34.47 | | 196.4 ± 22.94 | 132.4 ± 15.13 | 188.2 ± 28.3 |
| SOC | 131.7 ± 52.72 | | 177.56 ± 35.88 | 80.8 ± 14.27 | 133.1 ± 17.12 | 70.5 ± 14.33 | 118.3 ± 19.08 | 126.1 ± 40.34 | 183.89 ± 36.86 | | 90 ± 17.49 | | 147 ± 19.61 | 77.4 ± 15.36 | 130.2 ± 17.79 |
| SOP1 | 45.2 ± 27.66 | | 62.67 ± 21.09 | 47.7 ± 14.34 | 71.5 ± 24 | 47.1 ± 14.82 | 83.8 ± 21.8 | 52.8 ± 28.68 | 65.44 ± 32.58 | | 50.9 ± 15.55 | | 80.4 ± 24.99 | 49.1 ± 13.84 | 84.3 ± 22.37 |
| SOP2 | 38.9 ± 23.57 | | 51.11 ± 20.91 | 31.2 ± 13.68 | 52.7 ± 23.84 | - | - | 48.7 ± 26.75 | 53.78 ± 23.74 | | 34.5 ± 12.27 | | 56.3 ± 15.82 | - | - |
| TMA1 | 46.1 ± 15.39 | | 60.89 ± 14.43 | 62 ± 21.03 | 92.7 ± 25.21 | 88.8 ± 16.27 | 141 ± 33.68 | 58.3 ± 16.79 | 63.56 ± 18.7 | | 68.1 ± 16.25 | | 99.3 ± 18.58 | 91.7 ± 14.4 | 144.9 ± 32.46 |
| TMA2 | 43.3 ± 13.45 | | 58.56 ± 13.2 | 50.7 ± 22.31 | 90.8 ± 32.66 | - | - | 52.2 ± 16.09 | 63.11 ± 11.81 | | 55.2 ± 19.27 | | 93.7 ± 26.16 | - | - |
| PERI | 48.8 ± 16.92 | | 32.56 ± 16.67 | 20.9 ± 5.69 | 13.1 ± 13.85 | 23.4 ± 9.55 | 10.1 ± 8.28 | 32.9 ± 15.55 | 21.44 ± 15.78 | | 23.7 ± 8.51 | | 15.6 ± 15.36 | 26.1 ± 11.45 | 12.2 ± 8.69 |
| SHC | 23 ± 6.62 | | 30.44 ± 16.18 | 15.3 ± 3.59 | 23.9 ± 8.82 | 20.9 ± 5.95 | 22.5 ± 11.52 | 19.9 ± 5.82 | 25.33 ± 6.73 | | 16.2 ± 3.85 | | 25.2 ± 8.3 | 20.8 ± 6.81 | 25.3 ± 10.53 |
| Configuration | | | | 1.29 | | 1.24 | |  | | | 1.48 | | | .31 | |
| Configuration\*Role | | | | 6.40\*\*\* | | 21.63\*\*\* | |  | | | 4.57\*\*\* | | | 17.71\*\*\* | |
| Configuration\*Role\*Demand | | | | 1.28 | | 1.96t | |  | | | 1.15 | | | 3.00\*\*\* | |
|  |  | | |  | |  |  |  | | |  | | |  |  |
|  | **Sociometric Status** | | |  | |  |  | **Centrality** | | |  | | |  |  |
|  | Low | High | | Low | High | Low | High | Low | | High | Low | High | | Low | High |
| OOW | 22.86 ± 3.73 | 27.89 ± 4.85 | | 21.55 ± 5.11 | 29.19 ± 3.7 | 32.82 ± 7.68 | 41.32 ± 4.56 | 5.87 ± 0.38 | | 6.21 ± 0.25 | 5.85 ± 0.18 | 5.9 ± 0.21 | | 4.65 ± 0.25 | 4.91 ± 0.17 |
| OPSO | 40.63 ± 7.18 | 50.27 ± 4.8 | | 34.73 ± 7.67 | 50.66 ± 6.1 | 43.72 ± 5.08 | 62.42 ± 9.26 | 5.77 ± 0.24 | | 5.64 ± 0.16 | 5.51 ± 0.38 | 5.34 ± 0.51 | | 4.33 ± 0.13 | 4 ± 0.22 |
| SOC | 32.23 ± 11.56 | 45.18 ± 8.52 | | 21.35 ± 3.73 | 35 ± 4.3 | 24.65 ± 4.8 | 41.42 ± 5.9 | 5.65 ± 0.15 | | 5.28 ± 0.14 | 4.99 ± 0.34 | 5.21 ± 0.35 | | 3.77 ± 0.33 | 3.85 ± 0.13 |
| SOP1 | 12.25 ± 6.96 | 16.02 ± 6.64 | | 12.33 ± 3.65 | 18.98 ± 6.04 | 16.03 ± 4.64 | 28.02 ± 7.09 | 3.88 ± 0.23 | | 3.99 ± 0.33 | 4.6 ± 0.22 | 4.51 ± 0.23 | | 3.33 ± 0.24 | 3.33 ± 0.09 |
| SOP2 | 10.95 ± 6.22 | 13.11 ± 5.27 | | 8.22 ± 3.14 | 13.63 ± 4.8 | - | - | 4.18 ± 0.85 | | 4.09 ± 0.34 | 4.36 ± 0.27 | 4.45 ± 0.25 | | - | - |
| TMA1 | 13.05 ± 3.81 | 15.56 ± 3.94 | | 16.27 ± 4.6 | 24 ± 5.19 | 30.08 ± 5.08 | 47.65 ± 10.88 | 3.96 ± 0.32 | | 3.94 ± 0.09 | 4.49 ± 0.26 | 4.55 ± 0.25 | | 3.33 ± 0.13 | 3.47 ± 0.22 |
| TMA2 | 11.94 ± 3.56 | 15.21 ± 3.07 | | 13.24 ± 5.06 | 23.05 ± 7.3 | - | - | 3.87 ± 0.13 | | 3.95 ± 0.09 | 4.54 ± 0.22 | 4.63 ± 0.2 | | - | - |
| PERI | 10.22 ± 3.69 | 6.75 ± 3.67 | | 5.58 ± 1.74 | 3.59 ± 3.65 | 8.25 ± 3.47 | 3.72 ± 2.82 | 5.26 ± 0.26 | | 5 ± 0.33 | 3.84 ± 0.15 | 3.54 ± 0.15 | | 3.08 ± 0.21 | 2.92 ± 0.1 |
| SHC | 5.36 ± 1.33 | 6.98 ± 2.57 | | 3.94 ± 0.92 | 6.14 ± 2.13 | 6.95 ± 2.12 | 7.97 ± 3.67 | 3.7 ± 0.21 | | 3.79 ± 0.19 | 3.49 ± 0.25 | 3.58 ± 0.28 | | 2.82 ± 0.29 | 2.84 ± 0.1 |
| Configuration | | | | 1.52 | | 62.28\*\*\* | |  | | | 1.03 | | | 1982.49\*\*\* | |
| Configuration\*Role | | | | 5.68\*\*\* | | 22.10\*\*\* | |  | | | 38.25\*\*\* | | | 62.87\*\*\* | |
| Configuration\*Role\*Demand | | | | 1.04 | | 3.49\*\*\* | |  | | | 2.89\*\* | | | 2.52\* | |

\* p<.05, \*\*p<.01, \*\*\*p<.001, ± indication of plus or minus quantity



Figure 2. *Social network diagrams with means of emissions and receptions between operators for baseline, co-location and reduced crew size*

**Hypothesis 1b:** A reduction in crew size will alter the composition of the social networks

The number of edges (*F*1, 18 = 205.46, *p* < .01, ήp2 = .92), density (*F*1, 18 = 10.64, *p* < .01, ήp2 = .37), cohesion (*F*1, 18 = 64.35, *p* < .01, ήp2 = .78) and total interactions (*F*1, 18 = 9.83, *p* < .01, ήp2 = .35) of the entire networks were statistically significantly affected by crew size. This indicates that the structure of the networks fundamentally changed as a result of the reduced crew size. A reduction in the number of edges and increase in density was to be expected as there were fewer potential avenues for communication distribution with two operators removed from the team (see table 4 and figure 2). It was also hypothesised that the total number of verbal communications would decrease with a reduced crew size. However, despite this, the cohesion of the social networks was still significantly higher with a reduced crew size. As with the co-location with a full crew size (discussed above), the increase in cohesion indicates that a greater number of reciprocal communications occurred between a greater number of operators. This indicates that verbal information transition was more efficient, with greater one-to-one communication rather than information transitioning between multiple operators.

The interaction of crew size and role statistically significantly affected total emissions (*F*6, 126 = 21.63, *p* < .01, ήp2 = .51) and receptions (*F*6, 126 = 17.71, *p* < .01, ήp2 = .46) of operators. The total receptions of operators were also statistically significantly affected (*F*6, 126 = 3.00, *p* < .05, ήp2 = .13) by crew size, role and demand. This indicates that a reduction in total communications was not represented simply as a uniform reduction in the verbal communications of all operators, but rather it was specific to the operator role and the scenario demand. Post hoc analysis revealed OPSO and SOC had statistically significantly fewer emissions and receptions in the reduced crew size configuration than baseline. Whereas OOW and the TMA1 had statistically significantly more emissions in reduced crew size configuration compared to baseline and the TMA1 had significantly more receptions (see table 5 and figure 2). This reveals that both OPSO and SOC were required to send and receive information less in the reduced crew size configuration, seemingly due to the remaining TMA operator being facilitated to request and receive information required for the TMA process more efficiently. This is likely to have been facilitated by the co-location of the remaining TMA and SOP who were dependent on each other for task relevant information but were most distant with regard to network connectivity in the baseline scenarios. Further analysis revealed that OPSO had statistically significantly fewer receptions only in the reduced crew size low demand scenarios compared to the baseline low demand scenarios. This indicates that even with a reduced crew size, the command team had greater flexibility in the co-location configuration to tailor information flow depending on scenario demand, flexibility not afforded by the baseline configuration.

The size of the crew statistically significantly affected the sociometric status (*F*1, 126 = 62.28, *p* < .01, ήp2 = .33) and centrality (*F*1, 126 = 1982.49, *p* < .01, ήp2 = .94) of operators. The interaction between crew size and role also statistically significantly affected sociometric status (*F*6, 126 = 22.10, *p* < .01, ήp2 = .51) and centrality (*F*6, 126 = 62.68, *p* < .01, ήp2 = .75) of operators. Finally, the interaction between crew size, role and demand significantly affected the sociometric status (*F*6, 126 = 3.49, *p*<.01, ήp2 = .14) and centrality (*F*6, 126 = 2.52, *p* < .05, ήp2 = .11) of operators. This again indicates that a reduction in crew size did not impact the structure of verbal communication between the command team uniformly, it varied depending on operator role and demand.

Post hoc analysis revealed SOC had statistically significantly lower sociometric status in the reduced crew size configuration than in the baseline. OPSO, SOP1 and TMA1 had statistically significantly higher sociometric status in the reduced crew size configuration compared to baseline. In a DT there is a high reliance on sonar information, in the baseline configuration this resulted in an exceptionally high reliance on SOC as a broker of this information. The co-location configuration appears to have reduced some of this load as it has been distributed more evenly across the command team (e.g. one-to-one communications between TMA and SOP). Further analysis revealed all operators had statistically significantly lower centrality in the reduced crew size configuration than in baseline. However, some decreased to a much greater extent (e.g. OOW, OPSO and SOC) than others creating a more even distribution of centrality, indicating that the social network does not revolve around a particular operator(s).

**Hypothesis 2a:** Co-location will not alter the composition of verbal information exchange

The configuration statistically significantly affected the number of nodes (*F*1, 18 = 10.08, *p* < .01, ήp2 = .36), total emissions (*F*1, 18 = 6.38, *p* < .01, ήp2 = .26), diameter (*F*1, 18 = 8.56, *p* < .01, ήp2 = .32) and network density (*F*1, 18 = 18.74, *p* < .01, ήp2 = .51) of the information networks. A statistically significant (*F*1, 18 = 18.74, *p* < .01, ήp2 = .51) interaction between configuration and demand was also observed for total emissions.

Table 6. *Means and standard deviations of global information network metrics for baseline, co-location and reduced crew size*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | | | |  |  | Effect of  Co-location | Effect of Crew Size |
|  | Baseline | | Co-location | | Reduced Crew | |  |  |
|  | Low | High | Low | High | Low | High |  |  |
| Nodes | 42.80 ± 4.10 | 47.78 ± 7.86 | 49 ± 4.59 | 52.9 ± 4.65 | 50.5 ± 3.69 | 53.9 ± 2.38 | 10.08\*\*\* | 18.82\*\*\* |
| Edges | 615.60 ± 253.32 | 732.33 ± 257.72 | 694.4 ± 127.87 | 727.6 ± 102.51 | 677 ± 210.74 | 728.2 ± 134.93 | .21 | .10 |
| Density | 0.54 ± 0.21 | 0.60 ± 0.27 | 0.297 ± 0.05 | 0.2687 ± 0.05 | 0.2649 ± 0.05 | 0.2546 ± 0.04 | 18.74\*\*\* | 21.76\*\*\* |
| Cohesion | 2.90 ± 0.73 | 2.89 ± 0.73 | 3.6 ± 0.52 | 3.6 ± 0.52 | 3.5 ± 0.71 | 4.1 ± 0.57 | 8.56\*\*\* | 13.58\*\*\* |
| Total Interactions | 2409.20 ± 948.09 | 3693.67 ± 1471.06 | 2004.11 ± 526.57 | 2230.503 ± 202.37 | 1685.5 ± 928.8 | 2099.139 ± 665.85 | 6.38\*\*\* | 7.65\* |

\* p<.05, \*\*p<.01, \*\*\*p<.001, ± indication of plus or minus quantity

These results lead to a rejection of hypothesis 2a as the structure and type of the information communicated was different in the co-location configuration. The total number of emissions and overall network density was statistically significantly lower in the co-location configuration compared to baseline, but the number of nodes and density was statistically significantly higher in the co-location configuration compared to baseline (see table 6 and figure 3). This appears to indicate that despite no overall difference in the total number of interactions between operators (as revealed by the social network analysis), the volume of information contained in such interactions was lower resulting in a less cluttered (density) information network. However, despite this, a greater variety of information was exchanged by the command team (i.e. more nodes). It appears that co-locating operator’s dependent on each other for task relevant information (i.e. OPSO and SOC, TMAs and SOPs) has led to more efficient information exchange, which actually led to more information being passed. This may be due to the fact there were fewer repeat requests for information and/or clarification, as information was communicated more directly (i.e. on-to-one) rather than across multiple operators.

The total emissions (*F*1, 252 = 52.93, *p* < .01, ήp2 = .17), sociometric status (*F*1, 252 = 77.80, *p* < .01, ήp2 = .24) and centrality (*F*1, 252 = 134.85, *p* < .01, ήp2 = .35) of information were statistically significantly affected by configuration type. The total emissions (*F*13, 252 = 4.20, *p* < .01, ήp2 = .18), sociometric status (*F*13, 252 = 4.80, *p* < .01, ήp2 = .20) and centrality (*F*13, 252 = 1.98, *p* < .05, ήp2 = .10) of information was also statically significantly affected by the interaction of configuration and information type. This indicates that the structure of information was not uniformly impacted by the co-location configuration but rather that frequency and structure of particular information transition was differentially impacted. Post hoc analysis revealed the emissions and sociometric status of bearing, course and speed were statistically significantly lower in the co-location configuration compared to baseline, whilst all other information revealed no significant changes (see table 7 and figure 3). The command team’s knowledge of bearing, course and speed is critical to the development of tactical parameters as having such information provides awareness of what surrounds own submarine. The fact that the prevalence and importance of such information has dropped, at least with regard to the network structure might be concerning due to the criticality of such information. However, only the information node contact and priority had statistically significantly higher centrality in the co-location configuration compared to baseline. This indicates that all other information (including bearing, course and speed) revolved around contact and priority to a much greater extent. The command team’s knowledge of all contacts, particularly with respect to bearing, course and speed is critical for safe and effective operations.

 Figure 3. *Information network diagram with mean emissions between information nodes for co-location low demand DT scenario.*

Table 7. *Means and standard deviations of individual node social information metrics for baseline, co-location and reduced crew size*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Emission | |  | |  | | Sociometric | |  | |  | | Centrality | |  | |  | |
|  | Baseline | | Co-location | | Reduced | | Baseline | | Co-location | | Reduced | | Baseline | | Co-location | | Reduced | |
|  | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High |
| Bearing | 189.59 ± 105.06 | 343.21 ± 117.27 | 112.4 ± 45.9 | 161.8 ± 44.9 | 113 ± 66.09 | 161.9 ± 71.46 | 9.19 ± 4.76 | 15.54 ± 6.13 | 4.54 ± 1.48 | 6.1723 ± 1.56 | 4.36 ± 2.12 | 5.97 ± 2.36 | 28.04 ± 4.25 | 30.78 ± 5.20 | 30.49 ± 3.51 | 33.21 ± 4.17 | 30.59 ± 3.53 | 32.95 ± 3.71 |
| Contact | 116.48 ± 48.74 | 115.37 ± 72.81 | 127.9 ± 40.28 | 127.3 ± 43.69 | 117.5 ± 51.37 | 152.5 ± 72.19 | 5.60 ± 2.37 | 5.35 ± 3.58 | 5.31 ± 1.65 | 4.8731 ± 1.67 | 4.65 ± 1.93 | 5.64 ± 2.56 | 28.38 ± 5.41 | 29.08 ± 5.93 | 35.03 ± 4.05 | 37.65 ± 3.86 | 37.03 ± 3.08 | 38.83 ± 2.70 |
| Course | 141.35 ± 49.15 | 290.55 ± 95.69 | 104.2 ± 19.14 | 159.3 ± 52.55 | 113 ± 43.22 | 158.9 ± 46.64 | 7.05 ± 2.86 | 13.07 ± 4.31 | 4.33 ± 0.81 | 6.0873 ± 1.95 | 4.42 ± 1.44 | 5.89 ± 1.51 | 24.14 ± 3.70 | 28.03 ± 5.50 | 30.44 ± 2.47 | 33.29 ± 4.81 | 31.84 ± 3.58 | 34.93 ± 2.40 |
| Look | 59.30 ± 33.31 | 73.84 ± 39.70 | 58 ± 59.96 | 33.3 ± 10.03 | 55.7 ± 34.64 | 36.5 ± 15.09 | 2.91 ± 1.73 | 3.32 ± 1.72 | 2.38 ± 2.42 | 1.258 ± 0.3 | 2.14 ± 1.14 | 1.35 ± 0.54 | 23.66 ± 3.83 | 26.34 ± 6.44 | 28.62 ± 5.53 | 29.87 ± 4.3 | 30.49 ± 4.73 | 30.18 ± 2.62 |
| Merge | 143.10 ± 141.17 | 234.25 ± 254.42 | 44.3301 ± 23.84 | 34.01 ± 24.12 | 24.4 ± 23.16 | 28.48 ± 21.3 | 7.61 ± 8.48 | 10.93 ± 12.24 | 1.85 ± 1 | 1.3274 ± 0.92 | 0.96 ± 0.85 | 1.07 ± 0.78 | 24.85 ± 2.39 | 28.32 ± 6.02 | 26.60 ± 3.85 | 27.71 ± 3.29 | 25.48 ± 3.97 | 27.39 ± 2.29 |
| Periscope | 68.74 ± 34.45 | 65.47 ± 46.80 | 54.5 ± 36.96 | 31.2 ± 7.89 | 49.1 ± 21.7 | 30.4 ± 13.2 | 3.33 ± 1.75 | 3.09 ± 2.24 | 2.25 ± 1.46 | 1.2199 ± 0.42 | 1.94 ± 0.86 | 1.12 ± 0.44 | 24.19 ± 4.30 | 25.27 ± 3.59 | 28.23 ± 2.83 | 29.80 ± 2.03 | 29.14 ± 2.33 | 30.18 ± 2.42 |
| Priority | 53.67 ± 41.76 | 68.54 ± 64.57 | 62.8 ± 37.72 | 49.59 ± 23 | 54.8938 ± 53.63 | 51.8 ± 34.2 | 2.60 ± 1.95 | 3.27 ± 3.15 | 2.67 ± 1.71 | 1.9692 ± 1.18 | 2.22 ± 2.12 | 1.92 ± 1.23 | 22.71 ± 4.47 | 24.78 ± 5.38 | 28.41 ± 2.94 | 31.35 ± 2.51 | 29.94 ± 3.94 | 31.80 ± 3.62 |
| Solution | 129.40 ± 78.59 | 250.00 ± 136.43 | 128.7 ± 64.49 | 159.8 ± 36.53 | 107.5 ± 48.47 | 155 ± 69.39 | 6.44 ± 4.36 | 11.23 ± 6.50 | 5.49 ± 3.38 | 6.1847 ± 1.68 | 4.21 ± 1.74 | 5.72 ± 2.44 | 25.09 ± 3.21 | 28.63 ± 5.07 | 31.63 ± 3.09 | 35.05 ± 3.43 | 32.31 ± 2.59 | 35.64 ± 3.57 |
| Sonar | 84.10 ± 113.53 | 133.91 ± 124.88 | 67.3 ± 61.23 | 67.1 ± 76.33 | 69.8 ± 71.71 | 69.6 ± 91.43 | 4.14 ± 5.98 | 6.12 ± 5.34 | 2.67 ± 2.18 | 2.4675 ± 2.6 | 2.60 ± 2.37 | 2.50 ± 3.18 | 24.23 ± 3.86 | 27.15 ± 5.24 | 29.17 ± 4.58 | 31.06 ± 5.18 | 30.60 ± 5.08 | 30.01 ± 4.13 |
| Speed | 224.47 ± 103.97 | 408.89 ± 176.71 | 136.5 ± 27.98 | 177.59 ± 42.99 | 139.9 ± 61.78 | 159.12 ± 51.13 | 11.33 ± 6.39 | 18.52 ± 8.55 | 5.62 ± 0.93 | 6.8451 ± 1.72 | 5.46 ± 1.96 | 5.89 ± 1.68 | 27.36 ± 3.29 | 30.09 ± 6.13 | 30.75 ± 3.81 | 33.12 ± 3.57 | 31.88 ± 3.55 | 33.90 ± 2.69 |
| Sweep | 27.21 ± 28.02 | 32.14 ± 33.09 | 18.3 ± 12.92 | 21.43 ± 18.21 | 18.9 ± 8.39 | 18.97 ± 13.29 | 1.32 ± 1.37 | 1.40 ± 1.55 | 0.74 ± 0.48 | 0.8418 ± 0.71 | 0.76 ± 0.36 | 0.71 ± 0.5 | 19.69 ± 3.65 | 23.20 ± 4.69 | 23.09 ± 3.04 | 24.90 ± 3.5 | 25.36 ± 1.95 | 26.36 ± 2.61 |
| Depth | 36.37 ± 31.16 | 61.77 ± 68.23 | 26.5 ± 19.94 | 32.1 ± 17.21 | 24 ± 18.23 | 36.3 ± 20.67 | 1.77 ± 1.58 | 2.55 ± 2.62 | 1.09 ± 0.8 | 1.1993 ± 0.55 | 0.94 ± 0.7 | 1.33 ± 0.7 | 21.90 ± 3.76 | 24.56 ± 6.73 | 25.46 ± 2.74 | 28.66 ± 4.04 | 26.07 ± 3.72 | 29.57 ± 2.91 |
| Range | 125.26 ± 41.68 | 231.27 ± 125.49 | 75.9 ± 26.08 | 119.4 ± 35.72 | 76.34 ± 53.53 | 110.2 ± 43.97 | 6.17 ± 2.44 | 10.12 ± 4.60 | 3.10 ± 0.89 | 4.5162 ± 1.08 | 2.94 ± 1.66 | 4.07 ± 1.46 | 23.93 ± 2.87 | 27.11 ± 5.21 | 26.71 ± 3.21 | 29.06 ± 5.19 | 27.25 ± 4.31 | 29.78 ± 3.14 |
| Visual | 48.45 ± 27.11 | 49.65 ± 52.05 | 50.88 ± 24.04 | 46.10 ± 30.42 | 27.6837 ± 19.36 | 29.33 ± 24.36 | 2.31 ± 1.35 | 2.20 ± 2.31 | 2.09 ± 1.02 | 1.7775 ± 1.17 | 1.08 ± 0.74 | 1.08 ± 0.9 | 22.98 ± 2.83 | 24.67 ± 4.90 | 28.06 ± 1.15 | 28.98 ± 3.86 | 26.21 ± 4.04 | 27.66 ± 3.09 |
| Configuration | | | 52.96\*\*\* | | 53.80\*\*\* | |  | | 77.80\*\*\* | | 88.70\*\*\* | |  | | 134.85\*\*\* | | 177.53\*\*\* | |
| Configuration \* Concept | | | 4.20\*\*\* | | 4.03\*\*\* | |  | | 4.83\*\*\* | | 4.96\*\*\* | |  | | 1.98\* | | 3.13\*\*\* | |
| Config\*Role\*Demand | | | 1.64 | | 2.39\*\*\* | |  | | 1.24 | | 1.73 | |  | | .18 | | .27 | |

\* p<.05, \*\*p<.01, \*\*\*p<.001, ± indication of plus or minus quantity

Moreover, the capacity to prioritise is critical during a DT scenario, when there is a priority contact(s) to be tracked. This appears to indicate that the passing of information has become more effective, despite a reduction in volume, the structure of information transition appears to be more related to operational requirements. This again may be due to a reduction in repeat requests and/or confirmation of critical information that has been reduced by increase in on-to-one communication facilitated by the co-location of operator’s dependent on each other for task relevant information.

**Hypothesis 2b:** A reduced crew size will decrease volume of information exchanged

The size of the crew statistically significantly affected the number of nodes (*F*1, 18 = 18.82, *p* < .01, ήp2 = .51), total emissions (*F*1, 18 = 7.65, *p* < .01, ήp2 = .30), diameter (*F*1, 18 = 13.58, *p* < .01, ήp2 = .43) and network density (*F*1, 18 = 21.76, *p* < .01, ήp2 = .55). A statistically significant (*F*1, 18 = 4.43, *p* < .01, ήp2 = .20) interaction between configuration and demand was also observed for total emissions. This reveals that a reduction in crew size changes the structure and volume of information that is passed between operators, with the directions of change being similar to what was observed in the co-location configuration with a full crew size.



Figure 4. *Information network diagram with mean emissions between information nodes for reduced crew high demand DT scenario.*

The total number of emissions and overall network density was statistically significantly lower in the reduced crew size configuration compared to baseline, but the number of nodes and density was statistically significantly higher in the reduced crew size configuration compared to baseline (see table 6 and figure 4). This appears to indicate that even with a reduced crew size, the co-location configuration has created greater resilience within the command team with regard to the passing of critical information, potentially by making this process more efficient. This reliance is revealed by a greater variety of information being passed between operators when compared to baseline. Moreover, these effects were much more prevalent in the high demand scenarios than the low demand scenarios indicating that even with a reduction in crew size, the co-location configuration appears to have increased the capacity of the command team to efficiently pass relevant information, with a lower frequency of interactions between operators required to achieve this (as revealed by social network analysis).

The total emissions (*F*1, 252 = 53.80, *p* < .01, ήp2 = .17), sociometric status (*F*1, 252 = 88.70, *p* < .01, ήp2 = .26) and (*F*1, 252 = 53.80, *p* < .01, ήp2 = .18) of each node were statistically significantly affected by crew size. A statistically significant interaction between crew size and concept was also observed for emissions (*F*13, 252 = 4.03, *p* < .01, ήp2 = .17), sociometric status (*F*13, 252 = 4.03, *p* < .01, ήp2 = .17) and centrality (*F*13, 252 = 3.13, *p* < .01, ήp2 = .14). This highlights that a decrease in information prevalence and importance with regard to network structure was only observed for particular types of information. Moreover, the type of information that reduced in prevalence typically related to information that is most critical to the command team for the building of a tactical picture and for understanding the behaviour of the contact being tracked in the DT scenario. As the emissions and sociometric status of bearing, course, merge and speed were statistically significantly lower in the reduced crew size configuration compared to baseline (see table 7 and figure 4). The information node contact had statistically significantly higher centrality in the reduced crew size configuration compared to baseline. Further revealing that even with a reduced crew size, in the co-location configuration the command team were more efficient at centring information on what was critical to overall performance, which was knowledge of contacts.

**Hypothesis 3a:** Co-location will increase the volume of tasks completed

The type of tasks completed by the command team was the same during baseline, the co-location configuration, and the reduced crew size (for both high and low demand scenarios) as the fundamental task completed by operators did not change. The command team were required to complete a number of subtasks (e.g. detection and designation of contacts), which centred around informing 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 5 – for full task network metrics see baseline publication: Roberts et al., 2018). It is more pertinent to examine how the frequency of task completion was impacted by the control room configuration, as this provides some indication of whether overall productivity and performance was improved.

The frequency of task completion was statistically significantly affected by configuration (*F*1, 378 = 3.69, *p* < .05, ήp2 = .01), the interaction of configuration and task type (*F*20, 378 = 2.13, *p* < .01, ήp2 = .10) but not the interaction of configuration, tasktype and demand (*F*20, 378 = 0.99, *p* > .05). This indicates that the type of configuration had an impact on the volume of tasks that were completed by the command team. Moreover, the change in volume of tasks that were completed was not uniform across all task types, it varied as a result of the particular type of task. Post hoc analysis revealed that overall statistically significantly more tasks were completed in the co-location configuration than the baseline configuration. This indicates that the co-location configuration did, to some extent, improve command team performance as they were able to complete a greater volume of tasks (see table 8 and figure 5). This is potentially due to less time being allocated to pushing and pulling information of various types across the control room (as revealed by the social and information networks). Instead, more time could be allocated to task completion and greater overall productivity.

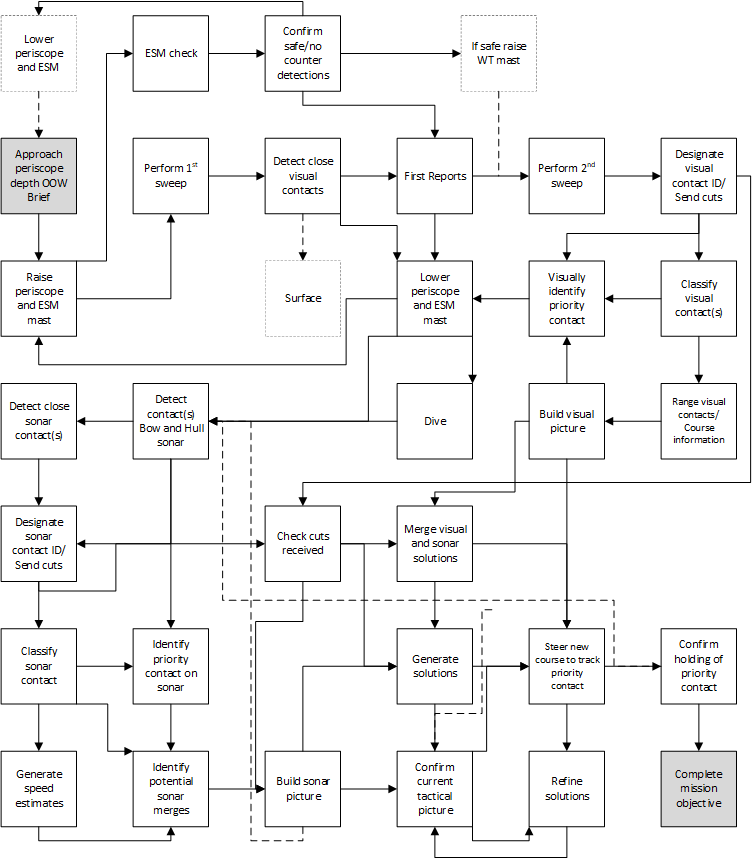


Figure 5. *Task network diagram for DT low and high demand scenarios (baseline, co-location and reduced crew size configuration)*

The tasks of attaining sonar speed estimates, checking cuts and refining solutions were completed statistically significantly more frequently in the co-location configuration than in baseline. This indicates that the increase in productivity was actually tailored to the particular operational requirements. In a DT scenario there is an emphasis on the command team to develop a good tactical picture and in particular develop a good understanding of the behaviours of the vessel being tracked. In the co-location configuration, the command team were able to generate more speed estimates, check sonar cuts (primary sensor being used when deep) and refine solutions more frequently. The behaviour of the contact being tracked in the DT scenario was constantly changing (i.e. speed and course changes). Therefore, the capacity of the command team to understand the contacts behaviour and achieve a high level of performance would have required regular speed updates, regular solution refinements and a regular checking of cuts (i.e. checking the contact was not being lost from the sonar sensors beams). An increase in the completion of these particular tasks reveals that the performance of the command team to achieve the primary mission objectives has increased in the co-location configuration.

Table 8. *Means and standard deviations of task completion frequency during high and low demand DT scenarios baseline, co-location configuration and reduced crew size.*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | DT |  |  |  |  |  |
|  | Baseline |  | Co-location |  | Reduced size |  |
|  | Low | High |  |  | Low | High |
| Detect Sonar Contacts | 5.3 ± 2 | 13.2 ± 4.39 | 6.6 ± 2.12 | 13.5 ± 2.42 | 6 ± 1.63 | 12.7 ± 2.63 |
| Designate Sonar Contacts | 4.7 ± 1.34 | 10 ± 3.53 | 5.6 ± 1.71 | 11.9 ± 2.28 | 5.3 ± 1.83 | 11.9 ± 2.08 |
| Classify sonar contacts | 4.7 ± 1.57 | 8.6 ± 3.44 | 3.6 ± 1.65 | 7.2 ± 3.19 | 3.1 ± 2.23 | 6.4 ± 2.27 |
| Sonar speed estimates | 6.3 ± 1.83 | 9.2 ± 3.12 | 6.5 ± 2.42 | 12.2 ± 2.57 | 5 ± 2.4 | 8.2 ± 2.39 |
| Check cuts | 1.9 ± 1.1 | 5.2 ± 3.43 | 5.1 ± 1.91 | 7 ± 3.74 | 2.9 ± 2.73 | 8.2 ± 2.78 |
| Sonar Merges | 2.5 ± 2.01 | 3.2 ± 1.69 | 3.8 ± 2.2 | 4.6 ± 2.41 | 2.8 ± 1.55 | 4.2 ± 2.39 |
| Sonar Solution | 5.4 ± 2.32 | 9 ± 2.87 | 4.1 ± 0.74 | 9 ± 0.67 | 4.2 ± 1.03 | 8.4 ± 1.58 |
| Refine Solutions | 3 ± 1.49 | 5.7 ± 3.37 | 4.3 ± 2.83 | 8.4 ± 4.12 | 5.4 ± 2.91 | 8.7 ± 3.47 |
| Change Sub parameters | 5.9 ± 2.56 | 8.3 ± 2.98 | 5 ± 2.49 | 8.8 ± 4.1 | 5.6 ± 2.46 | 7.4 ± 1.71 |
| Raise Periscope | 1.4 ± 1.26 | 1.1 ± 0.32 | 1.1 ± 0.32 | 1.1 ± 0.32 | 1.2 ± 0.63 | 1 ± 0 |
| Complete Sweep | 2.5 ± 1.78 | 0.4 ± 0.7 | 2 ± 0.82 | 0.3 ± 0.67 | 2.5 ± 0.71 | 0.1 ± 0.32 |
| Detect visual contacts | 3.5 ± 1.9 | 1.6 ± 1.07 | 2.9 ± 1.1 | 1.1 ± 0.32 | 3 ± 1.05 | 1 ± 0 |
| Designate visual contacts | 2.9 ± 0.99 | 1.4 ± 0.84 | 3.1 ± 1.29 | 1 ± 0 | 2.8 ± 1.23 | 1 ± 0 |
| Classify visual contacts | 3 ± 1.05 | 1.7 ± 0.82 | 2.3 ± 0.95 | 0.9 ± 0.32 | 1.9 ± 0.74 | 1 ± 0 |
| Range visual contacts | 2.9 ± 2.92 | 1.2 ± 1.23 | 1 ± 0.67 | 0.9 ± 0.32 | 0.7 ± 0.82 | 1.1 ± 0.32 |
| Visual solutions | 1.6 ± 1.07 | 0.6 ± 0.52 | 1.30 ± 0.67 | 0.9 ± 0.32 | 1.3 ± 0.82 | 0.9 ± 0.32 |
| Merge visual and sonar | 1.4 ± 1.35 | 0.7 ± 0.67 | 2.40 ± 1.17 | 1.00 ± 0.47 | 2 ± 1.05 | 1.1 ± 0.32 |
| Total tasks completed | 65.8 ± 10.72 | 92.1 ± 14.82 | 68.40 ± 11.04 | 100.2 ± 7.16 | 63.5 ± 8.78 | 91.60 ± 12.38 |
| Effect of Configuration |  |  | 3.69\* |  | .10 |  |
| Configuration\*task |  |  | 2.13\*\*\* |  | 2.62\*\*\* |  |
| Configuration  \*Task\*Demand |  |  | .99 |  | .99 |  |

\* p<.05, \*\*p<.01, \*\*\*p<.001, ± indication of plus or minus quantity

**Hypothesis 3b:** A reduced crew size will reduce the volume of tasks completed

It was anticipated that a reduction in crew size would lead to a significant reduction in volume of tasks completed by the command teams due to a reduction in resources. However, the frequency of task completion was not statistically significantly affected by crew size (*F*1, 378 = .10, *p* > .05), or the interaction of crew size, tasktype and demand (*F*20, 378 = 0.99, *p* > .05). This indicates that despite fewer resources the command teams were able to maintain levels of performance similar to those observed during baseline. From this it can be inferred that the efficiency of verbal information transition (as revealed by the social and information networks) has increased the capacity of the command team to such an extent that even with fewer operators the same number of tasks can be completed. Moreover, a statistically significant (*F*20, 378 = 2.62, *p* < .01, ήp2 = .12) interaction between crew size and task type was observed. Further analysis revealed the tasks of classifying sonar contacts, checking cuts and refining solutions were completed statistically significantly more frequently in the reduced crew size configuration than in baseline (see figure 5 and table 8). This further indicates that the performance of the command team was improved as they were able to undertake more tasks that were operationally relevant with a DT scenario. An increase in the completion of these particular tasks reveals that the performance of the command team to achieve the primary mission objectives has increased in the co-location configuration compared to baseline, even when two operators are removed from the command team.

**Hypothesis 4a:** Co-location will reduce operator workload

The spare capacity (Bedford scores) of operators was significantly affected by configuration type (*F*1, 126 = 7.254, *p* <.01, ήp2 = .054) in comparison to baseline, although no significant differences were observed with the interaction of configuration and operator role or configuration, operator role and demand (see table 9 and figure 6).

Table 9. *Means and standard deviations of Bedford scores for baseline, co-location configuration, and reduced crew size*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Baseline | | Co-location | | Reduced Crew Size | |
|  | Low | High | Low | High | Low | High |
| OPSO | 5.75 ± 2.37 | 6.25 ± 1.90 | 4.50 ± 2.01 | 5.20 ± 1.62 | 3.60 ± 1.17 | 6.00 ± 1.83 |
| PERI | 3.00 ± 1.63 | 1.80 ± .79 | 2.87 ± 1.26 | 3.01 ± 2.31 | 3.75 ± 1.78 | 2.70 ± 1.42 |
| SHC | 2.62 ± .99 | 3.30 ± .82 | - | - | - | - |
| SOC | 5.23 ± 1.97 | 5.60 ± 1.35 | 4.00 ± 1.63 | 4.90 ± 1.73 | 3.90 ± 1.37 | 5.50 ± 2.17 |
| SOP1 | 3.70 ± 1.70 | 5.55 ± 2.06 | 3.30 ±.95 | 4.50 ± 2.07 | 3.85 ± 1.29 | 6.10 ± 2.47 |
| SOP2 | 4.25 ± 1.90 | 5.50 ± 2.12 | 3.90 ± 1.20 | 4.90 ± 2.08 | - | - |
| TMA1 | 4.30 ± 1.77 | 5.80 ± 2.04 | 3.78 ± 1.01 | 5.21 ± 1.24 | 4.50 ± 1.08 | 7.40 ± 2.46 |
| TMA2 | 4.50 ± 1.27 | 6.20 ± 2.25 | 3.30 ± 2.00 | 4.70 ± 1.77 | - | - |
| Effect of configuration |  | | 7.25\* | | .013 | |
| Configuration\* Role |  | | .89 | | 2.32 | |
| Configuration\* Demand \* Role | | | .569 | | .509 | |

\* p<.05, \*\*p<.01, \*\*\*p<.001, ± indication of plus or minus quantity

Figure 6. *Means and error bars of Bedford scores for baseline, co-location configuration, and reduced crew size*

This indicates that the co-location configuration significantly increased the perceived spare capacity of all command team members in the command team and that such changes were observed uniformly regardless of role or scenario demand. It had been anticipated that increases in the efficiency of communications afforded by the co-location configuration (as indicated by the social and information networks) would reduce workload. This is a pertinent example of how removing production blocking mechanisms can increase the capacity of the team to complete work, and more importantly work efficiently, which has reduced the perceived workload of operators when completing the same scenarios as during baseline.

The workload of operators (NASA TLX) revealed no significant effect of configuration type or interactions with operator role and demand for perceived mental, physical and temporal demand or perceived effort and performance (see table 10 and figure 7). It was anticipated that perceived demand would decrease as a result of co-location, particularly as spare capacity increased (as revealed by Bedford scores). It appears that the increase in capacity afforded by the co-location configuration were utilised by the command team (i.e. a greater volume of tasks were completed) which meant that operators maintained similar levels of workload and performance by actually doing more work.

**Hypothesis 4b:** A reduced crew size will increase operator workload

The spare capacity (Bedford scores) of operators was not significantly affected by a reduced crew size or the interactions of crew size with demand and role, when compared to baseline (see table 9 and figure 6). It was anticipated that removing two operators from the command team would reduce spare capacity regardless of whether productivity was improved, simply due to the fact there are more tasks to be completed by fewer operators. However, a maintenance of capacity indicates that the co-location configuration has optimised performance, at least with regard to efficiency and productivity, to the extent that two operators can be removed from the command team with no change to the perceived spare capacity of the operators.

Table 10. Means and standard deviations of NASA TLX performance and effort scores for baseline, co-location configuration, and reduced crew size

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Performance** | | | |  |  | **Effort** | | | |  |  | |
|  | **Baseline** | | **Co-location** | | **Reduced Crew** | | **Baseline** | | **Co-location** | | **Reduced Crew** | | |
|  | **Low** | **High** | **Low** | **High** | **Low** | **High** | **Low** | **High** | **Low** | **High** | **Low** | **High** |
| **OPSO** | 15.20 ± 3.33 | 13.42 ± 3.58 | 13.40 ± 4.58 | 15.60 ± 2.41 | 14.20 ± 3.12 | 13.60 ± 1.78 | 11.50 ± 3.47 | 11.99 ± 4.00 | 11.30 ± 3.13 | 12.80 ± 2.82 | 10.60± 2.72 | 12.30 ± 4.00 |
| **PERI** | 13.90 ±2.51 | 14.56 ± 4.57 | 12.16 ± 5.08 | 12.45 ± 5.51 | 11.50 ± 3.98 | 11.70 ± 4.03 | 9.10 ± 4.01 | 4.86 ± 3.53 | 7.66 ± 2.55 | 7.52 ± 3.89 | 9.20 ± 2.97 | 5.20 ± 3.36 |
| **SHC** | 17.31 ± 2.06 | 16.98 ± 1.65 | - | - | - | - | 5.38 ± 3.80 | 6.38 ± 3.84 | - | - | - | - |
| **SOC** | 15.81 ± 2.77 | 14.91 ± 3.18 | 14.20 ± 4.61 | 12.60 ± 4.12 | 14.30 ± 3.74 | 12.50 ± 3.31 | 11.08 ± 4.59 | 11.75 ± 4.16 | 9.60 ± 2.32 | 11.60 ± 2.07 | 9.60 ± 2.67 | 12.20 ± 2.15 |
| **SOP1** | 14.50 ± 4.28 | 14.94 ± 2.53 | 14.10 ± 3.03 | 13.90 ± 2.60 | 14.90 ± 2.96 | 13.10 ± 3.63 | 9.00 ± 4.76 | 9.80 ± 3.82 | 9.20 ± 3.88 | 10.50 ± 2.99 | 8.90 ± 3.73 | 12.00 ± 4.11 |
| **SOP2** | 12.40 ± 3.27 | 14.28 ± 2.93 | 14.20 ± 1.87 | 12.30 ± 2.21 | - | - | 10.70 ± 3.20 | 12.89 ± 3.76 | 9.80 ± 4.64 | 12.80 ± 3.12 | - | - |
| **TMA1** | 14.50 ± 3.60 | 14.91 ± 2.51 | 12.80 ±1.93 | 13.70 ± 3.13 | 14.70 ± 2.75 | 12.10 ± 3.98 | 11.20 ± 4.44 | 12.32 ± 3.98 | 10.60 ± 3.53 | 11.60 ± 3.03 | 12.00 ± 2.49 | 12.60 ± 3.81 |
| **TMA2** | 14.80 ± 2.70 | 14.29 ± 4.08 | 14.10 ± 2.47 | 13.90 ± 1.73 | - | - | 11.70 ± 4.35 | 14.26 ± 3.95 | 8.90 ± 3.93 | 11.80 ± 2.70 | - | - |
| **Effect of Configuration** | | | 3.88 | | 6.87\* | |  | | .759 | | .102 | | |
| **Configuration\* Role** | | | .479 | | .571 | |  | | .631 | | .203 | | |
| **Configuration\* Demand \* Role** | | | 1.73 | | .785, | |  | | 680 | | .439 | | |
|  | | |  |  |  |  |  | |  |  |  |  |

\* p<.05, \*\*p<.01, \*\*\*p<.001, ± indication of plus or minus quantity

The workload of operators (NASA TLX) revealed no significant effect of crew size or interactions with operator role and demand for perceived mental, physical and temporal demand or perceived effort. The reduction in crew size led to a reduction in the perception of how well operators believed they were completing the task. It was anticipated that a reduction in crew size would significantly increase all workload measures. However, the results indicate that the co-location configuration has improved command team performance to such an extent that operator’s perception of workload was similar to baseline even with two operators removed. Although, a statistically significant effect of crew size on perceived performance (*F*1, 90 = 6.88, *p* < .01, ήp2 = .071) was observed. In the reduced crew size configuration operators perceived themselves to be performing worse than during baseline (see table 10 and figure 7). It appears that having a smaller command team has led the operators to believe their performance has decreased. This may be due to the operators having to work harder, although this view is not supported by the workload or spare capacity scores. Instead it appears that simply reducing the size of the command team leads to a reduction of perceived performance despite all indications (social, information, task and work load analyses) revealing that this was not the case.

Figure 7. *Means and error bars of NASA-TLX performance scores for Baseline, Co-location Configuration, and Reduced Crew Size*

**Discussion**

**The co-location Configuration**

In the co-location configuration, the effect of demand was similar to what had been observed in baseline, with a greater volume of communications between operators occurring (Roberts, Stanton & Fay, 2018). As with baseline, this suggests that a coping strategy for increased operational demand is to communicate more frequently. Communication can be a critical factor in determining the workload of a team, particularly if perceptual capacities for processing verbal information are being exceeded (Carletta et al., 2000; Salas et al., 2001, 2008; Stanton, 2011; Baddeley, 2000; Roberts & Cole, 2018). This was expected as the command team had a larger number of contacts to process in the high demand scenarios. However, the structure of the networks (edges, density and cohesion) remained similar regardless of demand. This suggests that the manner in which team knowledge was generated was similar in both the high and low demand scenarios (Klein, Moon, & Hoffman, 2006; Cooke, Gorman & Kiekel, 2008). However, the cohesion of the social networks was significantly higher in the co-location configuration compared to baseline, meaning that the distribution of information sharing was more evenly dispersed (Walker, Stanton, Salmon, & Jenkins, 2008). This offers greater flexibility as different command team members have different skills training and experience that can be distributed more effectively than in the baseline configuration (Alnuaimi, Robert, & Maruping, 2010).

The greater cohesion of the social networks is because the SOPs were no longer required to pass all information to the TMAs via SOC and OPSO, resulting in a more resilient network (Stanton et al. 20015a, b; Espevik et al., 2006). No overall significant differences were observed in total interactions between operators when comparing the co-location configuration. However, the differences between the high and low demand scenarios was much greater than what was observed during baseline, with the highest total emissions observed in the co-location high demand scenarios and the lowest in the co-location low demand scenarios (Roberts, Stanton, & Fay, 2018). It appears that the co-location configuration has led to greater flexibility of communication between command team members, which is critical for cognition at the level of the team (Fiore, Rosen, Smith-Jentsch, Salas, Letsky, & Warner, 2010; Cooke, Gorman & Kiekel, 2008). Greater capacity to communicate has been created but such capacity is only utilised when it is required operationally.

In the co-location configuration the sociometric status of the TMAs had significantly increased compared to baseline (Roberts, Stanton & Fay, 2018). During a DT operation, the command team is reliant on sonar data as the submarine is typically operating at depth (Bateman, 2011; Zarnich, 1999; Glosny, 2004; Champagne, Carl & Hill, 2003; Duryea et al., 2008; Holt, Noren, Veirs, Emmons & Veirs, 2009). However, it is the TMAs that are required to generate solutions for all contacts but also to provide regular updates on the priority contact that is being tracked. The co-location configuration has led to the TMAs becoming more critical to the command team process of tracking the contacts. Rather than being at the end of a trail of information transition (i.e. SOPs to SOC to OPSO to TMAs), the TMAs are now capable of requesting information from the SOPs as it is required to facilitate solution generation (Stanton, 2014; Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015; Loft, Sadler, Braithwaite, & Huf, 2015; Stanton & Roberts, 2017). This has also reduced SOC acting primarily as an information broker, resulting in a decrease in this operator’s sociometric status, which was very high during baseline. SOCs status in the command team is still high, but it appears this operator can focus on co-ordination and management responsibilities such as providing sonar updates on the priority contact which is critical for achieving mission objectives (Roberts & Stanton, 2018). Despite changes in command team functionality the operator with the highest centrality remained OOW as this operator is required to interpret the tactical picture and make tactical decisions (Roberts & Stanton, 2018; Dominguez, Long, Miller, & Wiggins, 2006). This indicates that whilst the co-location configuration has created greater flexibility and efficiency in terms of information exchange, fundamental team requirements (e.g. command structure) have remained stable.

The structure of the information networks revealed no significant differences between the high and low demand scenarios in the co-location configuration. Therefore, demand did not alter the structure in which information was passed as it did during baseline (Roberts, Stanton & Fay, 2018). This is despite an increase in the number of contacts to manage during high demand. This is potentially due to the attainment of team cognition being achieved more efficiently, even in high demand, when operating in the co-location configuration (Cooke, Gorman & Kiekel, 2008; Fiore, Rosen, Smith-Jentsch, Salas, Letsky, and Warner, 2010; Klein, Moon, & Hoffman, 2006). This may be due to the fact that operators could request information as it was required, rather than having to pass as much information as possible when the opportunity arose.

This is evidenced further by the significant increase in the centrality of operationally specific information such as ‘priority’ and ‘contact’. In the co-location configuration the relationship between these nodes is now one of the strongest in the information networks, much higher than during baseline. This further highlights that the command team is being more efficient in sharing information as it is knowledge of the priority contact being tracked that is most critical for achieving mission objectives (Bateman, 2011; Stanton & Roberts, 2017; Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015). Despite this, many of the most prevalent information nodes have not changed statistically with regard to sociometric status (e.g. contact, bearing, speed and course) when comparing the co-location configuration to baseline indicating the new configuration has not negatively affected the transition of critical information but rather has improved the transition of task relevant information (Sorenson & Stanton, 2013). However, the total emissions of bearing, course and speed were significantly lower in the co-location configuration compared to baseline (Roberts, Stanton & Fay, 2018). This again reveals increased efficiency as crucial information was not frequently being requested or repeated as it was passed between multiple operators in the command team. Information was more likely to be provided as it was requested as task dependent operators were co-located (Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015; Loft, Sadler, Braithwaite, & Huf, 2015).

In the co-location configuration, significantly more tasks were completed in the high demand scenarios, which again was to be expected due to the greater volume of contacts to be managed. The task completed most frequently were sonar tasks, in particular detection and designation. This is due to the fact the submarine was relying on sonar as the primary sensor when operating at depth (Bateman, 2011; Zarnich, 1999; Glosny, 2004; Champagne, Carl & Hill, 2003; Duryea et al., 2008; Holt, Noren, Veirs, Emmons & Veirs, 2009). The number of tasks completed by the command team in the co-location configuration was significantly higher than in the baseline configuration (Roberts, Stanton & Fay 2017). This indicates that the increased communication between command team members and better structured information connectivity has resulted in greater overall productivity. This suggests that the new configuration has removed the engineered restrictions which limited effective communication, reducing overall production blocking in the command team (Simms & Nichols, 2014; Suleiman & Watson, 2008; Stanton, Ashleigh, Roberts & Xu, 2003). The mechanisms that cause production blocking are related to unpredictable temporal lags with regard to information transition which disrupt the organisation and flexibility of idea generation in group contexts (Diehl & Stroebe, 1987; Nijstad, Stroebe & Lodewijkx, 2003).The co-location of the SOPs and TMAs and addition of an additional communication channel appeared to facilitate easier transition of operationally relevant information, affording greater overall productivity. The fact that these operators had greater capacity to communicate directly (i.e. not via OPSO and SOC), meant that two pairs of operators could simultaneously be synthesising information, which was not possible due to the production blocking caused by the bottleneck between OPSO and SOC (Roberts, Stanton & Fay, 2018; Stanton, Ashleigh, Roberts & Xu, 2003; Alnuaimi, Robert, & Maruping, 2010). This resulted in significant increasing to the completion of the tasks generate speed estimates and refine solutions in the co-location configuration. Being aware of the speed and position of the priority contact is critical for task success. It appears the command team were not just increasing overall productivity, but that additional capacity was targeted towards operationally relevant tasks. Interestingly, the perceived workload of operators remained unchanged when the co-location configuration was compared to baseline and spare cognitive capacity actually increased. This indicates that the co-location has increased the capacity of the command team, without increasing workload or impacting operator’s perception of performance.

**Reduced Crew Size**

In the reduced crew size condition, the structure of the social network varied greatly (fewer edges, lower density and cohesion) in the high demand scenarios, there was also a significantly greater number of total interactions. This indicates that with a reduced crew size the command team coped with demand by communicating more frequently, something that was also observed during baseline (Carletta et al., 2000; Salas et al., 2001, 2008; Stanton, 2011; Baddeley, 2000; Roberts & Cole, 2018). The command teams had significantly fewer interactions in the reduced crew size configuration (high and low demand) compared to baseline, suggesting that the capacity of the team had decreased as a result of losing two operators (Roberts, Stanton, & Fay, 2018; Salas, Burke, & Samman, 2001). Certainly, the capacity of the network decreased with fewer edges and greater density as a smaller number of operators were required to process the same volume of information. In the reduced crew size condition, OPSO had significantly higher sociometric status than all operators, this measure was particularly high in the high demand conditions (by far the highest observed across all studies). This appears to suggest that despite not being required to act as much as an information broker between the sound and picture room, OPSOs additional capacity has instead been utilised for team co-ordination and supervisory responsibilities – potentially making up for the shortfall of losing a TMA operator (Fiore, Rosen, Smith-Jentsch, Salas, Letsky, & Warner, 2010; Klein, Moon, & Hoffman, 2006). OPSO is typically responsible for assisting the OOW with the co-ordination and interpretation of the tactical picture (Roberts & Stanton, 2018). However, despite this, the volume of emissions and receptions for OPSO was significantly lower in the reduced crew size configuration compared to baseline but only in the low demand scenarios (Roberts, Stanton & Fay, 2018). This suggests the command team adopted different strategies and communication archetypes in the low demand vs. high demand reduced crew size scenarios, suggesting greater operational flexibility compared to baseline (Stanton et al. 20015a, b; Espevik et al. 2006).

In the low demand scenarios, it seems that tactical picture generation and monitoring the priority contact was processed more organically in a bottom up fashion, with less input from higher command (i.e. OOW, SOC, OPSO). Allowing higher command to focus on picture interpretation and decision-making processes (Klein, Ross, Moon, Klein, Hoffman & Hollnagel, 2003). However, during the high demand scenarios the command team appeared to be overloaded, demonstrated by the drastic increase in the sociometric status of nearly all operators. However, despite this the perceived workload and spare cognitive capacity of operators remained unchanged when the reduced crew size was compared to baseline. Although, the operator’s perception of their own performance decreased, suggesting the additional load did have some impact. This indicates that the co-location has increased the capacity of the command team, without increasing workload or impacting operator’s perception of performance. In these scenarios the tactical picture appeared to be driven in a top down fashion, with the strongest connectivity between operators being between OPSO and TMA1. It appears that the co-location configuration has created greater flexibility in terms of ways of working, particularly when coping with demand, something which was less observed in the baseline configuration (Roberts, Stanton & Fay, 2018). Overall, the sociometric status of SOC had significantly decreased in the co-location configuration compared to baseline, suggesting this operator may now have additional capacity, which could be used to interpret data from future technologies (Stanton, 2011; Duryea, Lindstrom, & Sayegh, 2008; Lee & Kantowitz, 2005). Once again, as with all scenarios in all experiments, the centrality of the OOW remained highest of all operators. This operator is responsible for interpreting all information and making tactical decisions (Dominguez, Long, Miller, & Wiggins, 2006). It is important that the co-location configuration with reduced crew size does not remove the OOW from being central to the command team; this does not appear to have been the case, although centrality is more evenly distributed across the command team as a whole.

When examining information composition, the effect of demand in the reduced crew size configuration was different to what was observed during baseline as no significant difference was observed in total interactions between information across high and low demand scenarios (Stanton, Roberts & Fay, 2018). However, in the high demand co-location configuration there were significantly more nodes and edges (despite fewer overall interactions), indicating greater connectivity between information. Suggesting the new configuration has facilitated greater flexibility in terms of how information was structured when being passed between operators but that is less impacted by operational demand (Stanton, Roberts & Fay, 2018). It appears the co-location of task dependent operators has facilitated information transition as it is requested, rather than when an operator had the opportunity to pass information, removing production blocking mechanisms (Stanton, Ashleigh, Roberts & Xu, 2003). This is further verified by the fact that the density of the networks was significantly lower in the co-location when compared to baseline. Information is no longer being repeatedly passed via multiple operators, in different orders and containing information not requested. This again highlights how the configuration of a team and supporting technology can greatly improve the effectiveness of overall team functionality (Stanton et al. 20015a, b; Espevik et al., 2006). Effective communication between operators is critical for the attainment of team cognition, creating more structured information transition (i.e. less interruption and information requesting) regardless of demand can help macrocognition building processes (Fiore, Rosen, Smith-Jentsch, Salas, Letsky, & Warner, 2010; Klein, Moon, & Hoffman, 2006). Overall, the information that was critical to operators in baseline (e.g. bearing, contact and speed) has remained the most critical in the reduced crew size (i.e. the highest sociometric status). However, the emissions of such information has significantly decreased, making the centrality of all nodes similar. This appears to be due to such information being communicated less as information was passed more efficiently (i.e. information was not being lost or repeated via multiple operators). This is further exemplified by the fact that the information node ‘contact’ had significantly increased in terms of centrality, as it is knowledge of contacts (including priority) that is critical to the command team.

In the reduced crew size configuration, the number of tasks completed in the high demand scenarios significantly increased as the command team had a greater volume of contacts to manage. The tasks that were typically completed most frequently were sonar tasks, as this is the primary sensor used during a DT (Bateman, 2011; Zarnich, 1999; Glosny, 2004; Champagne, Carl & Hill, 2003; Duryea et al., 2008; Holt, Noren, Veirs, Emmons, & Veirs, 2009). There was no significant difference in the number of tasks performed when comparing the reduced crew size configuration to baseline, which suggests productivity has at least been maintained despite fewer operators (Roberts, Stanton, & Fay, 2018). However, certain tasks were performed more frequently in the reduced crew size configuration compared to baseline with a significant interaction between task type and crew size observed. Smaller team sizes have frequently been demonstrated to be more productive due to increased accountability and supervision (Simms & Nichols, 2014; Suleiman & Watson, 2008; Stanton, Ashleigh, Roberts & Xu, 2003; Watkins, Mukherjee, Onder, & Mattila, 2009; Parasuraman & Manzey, 2010). However, it also appears that the co-location of operators has increased efficiency by removing engineering based constraints which caused production blocking which typically results in inadvertent suppression of ideas, distraction and/or forgetfulness, contributing to reductions in overall productivity (Stanton, Ashleigh, Roberts & Xu, 2003; Watkins, Mukherjee, Onder, & Mattila, 2009).

**Summary and conclusions**

The current work compared a current operational submarine control room configuration to a new co-location configuration with a full command team and a reduced size command team during the completion of DT scenarios. The results indicate that co-locating operators dependent on each other for task relevant information has altered the strategies undertaken by the command team when passing information, affording greater structure and efficiency that led to greater overall productivity in terms of task completion (Roberts, Stanton & Fay, 2018). This offers great support to the view that team control room configurations can greatly impact the functionality of a team working together in pursuit of higher goals (Espevik, Johnsen, Eid, & Thayer, 2006; Lee & Kantowitz, 2005; Stanton, Rothrock, Harvey, & Sorensen, 2015). The impact of the effect was so pronounced that even command teams with a reduced number of operators were more productive than the baseline configuration when completing some tasks (Roberts, Stanton & Fay, 2018). This supports previous work that has examined the impact of a co-located configuration when performing a return to periscope depth (Roberts & Stanton, 2019). It appears that the removal of engineering constraints that have governed operator positions in control rooms for almost a century led to a reduction in production blocking (Simms & Nichols, 2014; Suleiman, & Watson, 2008; Stanton, Ashleigh, Roberts & Xu, 2003; Parasuraman & Manzey, 2010). Increasing the efficiency of communications between operators and information organisation has the potential to greatly improve team cognition process (Cooke, Gorman & Kiekel, 2008; Fiore, Rosen, Smith-Jentsch, Salas, Letsky, & Warner, 2010; Klein, Moon, & Hoffman, 2006).

It is important that the results of the current work are utilised with caution, the scenarios included in the current study were purposely designed to be ‘routine’ and unclassified. It is unclear what the impact of non-routine events might be and what the resilience of the sociotechnical system might be when faced with unexpected scenarios, particularly with a reduced crew size. The primary aim of the current work was not to state a case for reduced crewing but rather to examine if additional capacity could be realised. It certainly appears that an increase in the capacity of the command team was realised, at least through optimization, demonstrated by the comparability of the reduced crew size to baseline. However, future research should examine if such benefits can be realised over longer periods, with greater variances in scenario predictability and/or demand. Moreover, the current work promotes a drive to examine novel designs to additional aspects of the control room (e.g. role/task allocation and interface designs). This has the potential to facilitate a combination of functionality between operators currently dependent on each other for task relevant information. A weakness of the current work is that a mid-fidelity simulator and novice participants were used. Previous work has highlighted substantial differences between novice and expert participants (Loft, Morrell, Ponton, Braithwaite, Bowden, & Huf, 2016). Although, the use of novice participants for command and control studies has been shown to be effective in previous research (Walker, Stanton, Salmon, Jenkins, Rafferty & Ladva, 2010), including research completed in the current simulator (Roberts, Stanton & Fay, 2018; Stanton & Roberts, 2017). Nevertheless, it is important that such work is used to inform testing of concepts in higher fidelity environments with expert teams, to fully appreciate the impact of design changes on complex sociotechnical systems. A further weakness of the current work is that despite the task frequency, workload and cognitive capacity of operators being assessed, the quality of work completed by the operators was not examined objectively, (e.g. evaluation of tactical picture accuracy). A future research endeavour should be examination of how performance at the level of the team can effectively be examined to understand the impact changes to control room design have on such measures. Further investigation of this is warranted to validate the improvements in efficiency and to ensure that an increase in productivity is not to the detriment of overall safety (Watkins, Mukherjee, Onder, & Mattila, 2009). A final point of consideration is the quasi-experimental design. The current work attempts to balance ecological validity with experimental control. This can maximise the applied value of the work but it can also, to some extent, limit validation of theory. The data suggests that a reduction in production blocking was facilitated by the co-location of operators and addition of a communication channel, leading to an overall increase in productivity. However, the co-location of operators may have created the conditions for greater implicit co-ordination facilitated by an increase in non-verbal communication and gesturing. This may be a contributing factor to the changes in the composition of the social, information and task networks that were observed. Future work should seek to measure such processes to ascertain the extent to which additional factors beyond production blocking contribute to an overall increase in team productivity when examining control room configurations. Nevertheless, the current work offers insight into where future control room design can benefit from utilisation of a sociotechnical perspective to maximise the potential affordance of future technological advances in terms of sensor capabilities.

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