**Better Together? Investigating new control room configurations and reduced crew size in submarine command and control**

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**Abstract**

The separation of the sound and control rooms in Royal Navy submarines seems to be artefactually reducing the effectiveness of information transition and the overall productivity of the team. A proposed integrated sound and control room was tested in three scenarios: Return to Periscope Depth (RTPD), Inshore Operations (INSO) and Dived Tracking (DT). The activities and communications of a team of serving submariners were recorded in a control room, in a single case study design, comparing co-location and reduced crewing with a baseline of the separate sound and control room configurations that is representative of current submarines. The Event Analysis of Systemic Teamwork (EAST) method was used to examine changes in social, information and task networks. In general terms, the co-location of the submariner team led to more efficient communication and completion of tasks. Reducing the crew was more challenging in the higher demand scenarios.

**Practitioner summary**

There are constraints acting on control rooms, both in terms of physical space and crew size. This study compared conventional control room with a co-location and reduced crew in turn. Teamwork improved in the collocated control room but the reduced crew struggled most under conditions of high demand.

**Key words:** Submarine, Control room, Teamwork, Communications, Networks

**Introduction**

A sociotechnical system is defined as the interaction of human operators and technology, with growing interdependence in pursuit of purposeful, goal-directed, activities (Walker, Stanton, Salmon, & Jenkins, 2008). Advancements in technology, computing processing and sensor capacities have led to the development of highly complex sociotechnical systems, of which a submarine control room is an excellent example (Stanton, 2014; Stanton & Roberts, 2018). The basic configuration of submarine control rooms has remained similar across a century of operations (Stanton, 2014), constrained by engineered restrictions (e.g., hull penetrating periscopes) rather than optimal sociotechnical performance (Duryea, Lindstrom & Sayegh, 2008). In almost every domain however, there is a current drive is to optimise the performance of teams via technology to maximise output and productivity (Brynjolfsson & Hitt, 2000; Devaraj, & Kohli, 2003). The continuing advancement of technology means that sociotechnical systems are set for revolutionary changes in ways of working to increase capability (Roco & Bainbridge 2003; Showalter, 2005). Moreover, in submarine control rooms for example, extant engineering based design constraints are being overcome, such as the introduction of optronics masts facilitating new considerations for control room positioning aboard submarines (Hiskett, & Lamb, 2014). The drive to optimise sociotechnical system performance is evident across many domains including surface vessels (Lützhöft, & Dekker, 2002; Negahdaripour, & Firoozfam, 2006), aircraft (Rudisill, 2000; Bruce, Rice, & Hepp, 1998; Stanton, Harris, & Starr, 2016) and gas/electric/nuclear power plants (Santos, Teixeira, Ferraz, & Carvalho, 2008; Stanton, Salmon, Walker & Jenkins, 2009). It is critical that such advancement includes evaluation of new technologies and ways of working from a sociotechnical systems perspective (Stanton, 2014).

A previous study by Stanton & Roberts (2018) catalogued the performance of an expert submarine command team in current ways of working across a range of routinely performed operations. Recommendations included that optimal control room configurations should reduce the information-brokering load placed upon the Operations Officer and Sonar Controller when passing information from the sound room to the picture room. As this had the potential to be a bottleneck, limiting effective information transition (Stanton, Roberts & Fay, 2017; Roberts, Stanton & Fay, 2017; Roberts & Stanton, 2018) as illustrated in figure 1a. Furthermore, increasing information exchange between the Sonar Operators (SoPs) and Target Motion Analysis operators (TMAs), two clusters of operators highly dependent on each other for task completion (as illustrated in figure 1b) has the potential to improve overall command team capacity (Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015; Loft, Sadler, Braithwaite, & Huf, 2015). Finally, co-locating operators who routinely shared information was highlighted as potentially freeing additional capacity and increasing overall productivity (Roberts & Stanton, 2018). However, to our knowledge no further investigation of control room configuration has been conducted to examine such recommendations.

Contemporary UK submarines have separate sound rooms and control rooms (figure 1a), which is a legacy back to the time when sonar information was solely in auditory form and before noise cancelling headsets were commonplace. This meant that a quiet room was needed for the sonar operators to listen out for new contacts. Contemporary sonar information is displayed on visual ‘waterfall’ displays as well as auditory headsets. This means that, together with advances in noise cancelling technology, the sound room can be combined with the control room to overcome some of the information communication bottlenecks identified by Stanton & Roberts (2018). A possible new arrangement is illustrated in figure 1b, as the information on new contacts gathered by the Sonar Operators has to make its way to the Time-Motion Analysts. By sitting the Sonar Operators and Time-Motion Analysts side-by-side many of the barriers observed in the baseline study should be removed.

OOW

SoP1

SoP2

SoC

OpsO

ShC

Peri

TMA1

TMA2

1a

ShC

Peri

OOW

OpsO

SoC

TMA1

SoP1

TMA2

SoP2

1b

FIGURE 1. Current control room arrangement (1a – baseline study) and proposed control room arrangement (1b – study in this paper) with communication channels indicated by connections between nodes. [Key: SoP = Sonar Operator, SoC = Sonar Controller, OOW = Office of the Watch, ShC = Ships Control, Peri = Periscope Operator, OpsO = Operations Officer, TMA = Time-Motion Analyst] Details of the work are contained in table 1.

In contemporary sound rooms (see Figure 1a), sonar data is gathered by the SoPs, who are being managed by the SoC (such as differentiating between man-made and biological sounds as well as between sounds from same and different sources). The SoC decides which contact data (e.g., surface ships and submarines) are sent to the TMAs in the control room, through discussions with the OpsO and OOW. The OpsO manages the tactical picture development, being undertaken by the TMAs, to keep the OOW updated on the submarines safety, covertness and mission. On the basis of this picture, the OOW instructs ShC on the speed, course and depth of the submarine. If the submarine is at periscope depth, the OOW might instruct the Peri to raise the periscope so that the tactical surface picture can be verified.

In the proposed new arrangement of the command team (see Figure 1b), all personnel would be in the same room (so there would no longer be a separate sound room). The major change would be to site the SOP and TMA personnel next to each other so that they could interact directly, under the supervisor and quality control of the SoC and OpsO. The work would remain largely unchanged with the exception that, once permission to pass a contact from SoP to TMA had been approved, the SOP and TMA would be allowed to interact directly rather than through the SoC and OpsO, as was previously the case. It is anticipated that this relatively simple change in team structure and location would relieve the bottleneck in communications observed by Stanton and Roberts (2018).

It has been proposed that a reduction in output and performance in team environments is due to production blocking (Stanton, Ashleigh, Roberts & Xu, 2003). This is an extension of social loafing theory, which refers to instances where individuals working in a group exert less effort than when working alone (Simms & Nichols, 2014; Stanton, Connelly, Prichard and van Vugt, 2002). It could be argued that the design of team structures and communication channels can unwittingly create bottlenecks in team processes, whereby individual team members may be blocked from contributing to the team processes. This may be thought of as a form of engineered social loafing (Roberts et al, 2019). This phenomenon increases in technology-supported and location distributed teams, with the potential for overall productivity loss (Simms & Nichols, 2014; Suleiman, & Watson, 2008). Production blocking occurs when verbal communication is limited (i.e. only one person can talk at a given time), leading to inadvertent suppression of ideas, distraction and/or forgetfulness, contributing to reductions in overall productivity. An example of this in a submarine control room is that all SoPs (of which there can be up to 6 in a command team) are required to share information via one individual – the sonar controller (Roberts, Stanton & Fay, 2017). This also has the potential to exceed the cognitive capacities of the operator acting as an information broker (Roberts & Cole, 2018). A further example of this is the requirement of the OOW to provide supervisory support across two different rooms within the command space, potentially resulting in reduced motivation from neglected operators depending upon operation type. However, a key question is whether teams of individuals overtly reduce output or whether the engineering of the sociotechnical system itself restricts output (Stanton, Ashleigh, Roberts & Xu, 2003). The appearance of bottlenecks in the social network analysis of command teams suggests that the physical design of the system plays a critical role in reducing productivity (Roberts, Stanton & Fay, 2017).

The configuration of a control room space can impact upon how communication takes place and ultimately how effectively a team can perform (Stanton, Rothrock, Harvey & Sorensen, 2015a, b; Espevik, Johnsen, Eid, & Thayer, 2006). Operators do not reduce productivity solely due to social factors, but rather the design of sociotechnical systems (e.g., configuration and distribution of operators) actively constraining the manner in which command teams function (Stanton, Rothrock, Harvey & Sorensen, 2015a, b). A network archetype can be defined as a group of interconnected things that facilitates the exchange of information to achieve global objectives (Griffin, Young, & Stanton, 2010; Provan, Fish, & Sydow, 2007). Network archetypes have been demonstrated to be an indicator of team performance, providing an understanding of where bottlenecks in the system might be and how resilient a system might be (Stanton, Rothrock, Harvey, & Sorensen, 2015a, b; Houghton, Baber, McMaster, Stanton, Salmon, Stewart, & Walker, 2006). It is therefore pertinent to examine how different control room configurations might affect the prominence of particular network archetypes and the impact this has upon functionality and performance (Stanton & Roberts, 2018). Particularly with regard to communication (Salas, Burke & Samman, 2001; Carletta, Anderson & McEwen, 2000).

In many domains economic costs have been lessened by reducing manning requirements (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 can improve overall efficiency (Watkins, Mukherjee, Onder, & Mattila, 2009). Therefore, command teams with greater numbers of operators cannot increase productivity unless control rooms are flexible enough to accommodate different team configurations and operationally specific ways of working (Stanton, Roberts & Fay, 2017). An investigation of crew size therefore, is not necessarily concerned with a manning reduction, but whether command team capacity is being optimally utilised. However, a primary consideration is the impact a reduction in crew size has upon team performance and operational safety (Salotti, Heidmann, & Suhir, 2014). The purpose of the research contained within the current paper is to examine a novel control room configuration with a standard and reduced crew size, to baseline ways of working previously documented by Stanton & Roberts (2018). This will include a comparison across multiple scenario types to understand how control room design affects team activities across different operations.

**Method**

To facilitate direct comparison, the methods employed in the current studies are similar to those employed during the baseline study (Stanton & Roberts 2018). To avoid repetition, an overview of the method is provided with an emphasis on changes made to the testing procedure for the current studies. A single case study design approach was used, mainly because of the difficulty in gaining access to serving submariner teams.

**Participants**

A team of nine currently operational submariners were recruited from the Royal Navy (RN), participation was voluntary. The command team was identical to that of baseline except for a different Commander due to logistical issues (who took the role of Officer of the Watch). In the reduced crew study two members of the command team were removed (2 x Able Ratings). Security issues limited the collection of demographic information. All participants were male, met requirements to be operational submariners and had an age range of 25 – 46. The study protocol received ethical approval from the University of Southampton Research Ethics Committee (Protocol No: 10099) and MoDREC (Protocol No: 551/MODREC/14).

Table 1. Key roles and overview of main duties

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

**Equipment – The submarine Control Room Simulator**

The submarine simulator that had been built to represent a currently operational Royal Navy (RN) submarine (see Roberts, Stanton & Fay, 2015 for a fuller description) for baseline studies was reconfigured to match the new testing requirements (see figure 1 and table 1). The plan for the reconstruction of the simulator was based upon analysis of data collected during baseline studies and thorough review of findings by numerous Subject Matter Experts (SMEs). SMEs included RN personnel, Human Factors researchers and industry partners involved in the design and manufacture of British submarines (e.g., BAE Systems, Thales and Atlas Electronic). The key issues observed with control room configuration and recommendations from SMEs are summarised in figure 2 and table 1. Aside from the change in configuration, all other aspects of the simulator remained the same. The same positions as baseline were also used including; two Sonar Operator stations (SoP), two Target Motion Analysis stations (TMA), a Sonar Controller station (SoC), an Operations Officer station (OpsO), a Periscope station (Peri), a Ship Control station (ShC) and an Officer of the Watch station (OOW). In the reduced crew study, one SOP and TMA were removed, primarily as these roles involved duplication, so afforded the best maintenance of capacity assessment. The same unclassified set of scenarios from baseline were used. These included High (H) and low (L) demand versions of Return to Periscope Depth (RTPD), Inshore Operations (INSO) and Dived Tracking (DT). The high demand scenario versions were created by changing the number and behavioural complexity of surrounding contacts

**Design and Procedure**

As with the baseline study, in the co-location and reduced crew studies, a single case study approach was used. The independent variables were scenario type (RTPD, INSO and DT) and scenario demand. The dependant variables included all communications between members of the command team and task completed. Informed consent was attained and participants were assigned station roles based upon their operational role within the RN. Once an hour long simulator familiarisation had been completed participants were informed that the first scenario would begin with an OOW briefing and recording devices were started. A short break and refreshments were provided between scenarios. The command team completed all scenarios (order: RTPDL, DTH, INSOH, DTL, RTPDH and INSOL). Each scenario lasted approximately 45 minutes. At the end of the testing day participants were provided with a full debrief and thanked for participating.

The single case study approach is used when trying to study natural phenomena in the operational environment, particularly when trying to understand complexities and nuances of why work is undertaken in a particular way. Ergonomics abounds with examples of studies in aviation (Stanton et al, 2019), rail (Salmon et al, 2013; Stanton and Baber, 2009), police (Jenkins et al, 2011) and military (Rafferty et al, 2010; Stanton et al, 2010). Case studies enable an in-depth exploration of the data, which can be particularly insightful when studying team behaviour (Stanton et al, 2019). In the particular studies reported in this paper, it is extremely difficult to gain access to real operational submariner teams, which is an additional reason for the single case study approach.

**Figure 2.** *Control room configurations.* Figure 1a is the baseline configuration. The critical issues that required addressing based upon SME recommendations included: **1.** The 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 requirement for shared awareness between the sound room and control room. Figure 1b is the novel configuration proposed by the SME panel to be investigated. Figure 1c. is the co-location configuration with a reduced crew size (SoP1 and TM1 removed).

**Table 1.** Design issues revealed from baseline analysis and recommendations for new configuration

|  |  |  |
| --- | --- | --- |
|  | Issue | Recommendations |
| 1 | A bottleneck in information flow between SoC and OpsO. | Position OpsO and SoC next to each other with visibility of each other’s screens. This issue is also relieved by placing TMAs and SoPs next to each other. |
| 2 | The number of screens (in different rooms) OOW needed to observe. | Position OOW in a location where they can view the work being completed by all operators. |
| 3 | A reliance of TMAs on information from SoPs to generate solutions (informing tactical picture). | Position TMA and SoPS operators next to each other so they can directly share information and view each other’s screens. |
| 4 | A lack of shared awareness by the command team, particularly between the sound room and picture room. | Remove separate rooms for the SoPS and TMAs creating an open workspace for all operators with greater shared information and tasks. |
| 5 | An assessment of spare capacity in the command team | Removal of two operators duplicated within the command team (a SoP and TMA) |

**Analysis of Data**

The analysis conducted was identical to baseline studies to facilitate direct comparison (see Stanton & Roberts, 2018 for full details). The analysis used a shortened form of Event Analysis for Systemic Teamwork (EAST: Stanton, 2014). EAST models complex collaborative systems through a network approach. The social networks examine communications between ‘agents’ within the command team. Information networks describe the information passed between ‘agents’. Task networks describe tasks and their interdependencies. The networks are developed directly from the raw data of video and verbal recordings. These networks were modelled using AGNA software (version 2.1.1 – a software program for computing the Social Network metrics). A number of metrics were derived from AGNA allowing a quantitative assessment of the networks to accompany the descriptive models. A collection of global node metrics were calculated as defined in table 2.

Table 2. Overview of global metrics generated by EAST analysis

|  |  |
| --- | --- |
| Metric | Definition |
| Global | **Applied to the whole network** |
| 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 network divided by number of possible connections |

These global metrics describe the structural aspects of the networks and are useful for showing the macro effects of changes made in the studies described in this paper. There are also nodal metrics that describe the effects on individual agents, tasks and information nodes but these are not used in these case studies paper.

**Results**

Social network analysis

In the co-location configuration RTPDH had the highest number of edges, even when compared to baseline scenarios (see figure 3 and table 2). However, the lowest number of edges was observed during the DTH co-location scenario. This suggests that whilst the new configuration facilitates greater connectivity between all operators, such connectivity is not necessarily utilised. This is further evidenced by the greater range (Base = 0.08, Co-locate= 0.16) and variability of network cohesion between scenarios observed in the co-location configuration compared to baseline. Overall, in the reduced crew size configuration, the number of edges was lower, which is to be expected as there were less operators (so 14 less potential edges). The highest number of edges observed in the reduced crew size configuration was in RTPDL and the lowest number was observed in the RTPDH (see figure 1 and table 2). It appears the RTPD scenarios in the reduced crew size configuration revealed two different strategies for coping with the lost operators; increased connectivity between operators (more edges) or less connectivity between operators (less edges), with strategy choice mediated by scenario demand. This is further emphasised when comparing manipulation 2 to baseline, with the reduction in edges observed (RTPDL = 6, RTPDH = 14, INSOL = 0, INSOH = 13, DTL = 11, DTH = 6) dependant on scenario type and demand. The cohesion of the networks is notably greater across all scenarios in the reduced crew size (compared to baseline), whilst the density of the networks remains stable (see table 2). This indicates that the increase in total number of communications observed across all scenarios has been spread across more operators.

Overall, the data indicates that the new configuration appears to facilitate more flexible command team communication that is dependent on operational requirements. The new configuration clearly facilitates greater connectivity between all operators, but such connectivity is not always utilised. The total interactions between nodes is higher in the co-location configuration compared to baseline across all scenarios. This suggests that the new configuration increased the capacity of operators to communicate, potentially due to the fact that the bottleneck in communications between OpsO and SoC observed in baseline has been removed via the co-location of the SoPS and TMAs. The increase in communication capacity was also demonstrated in the reduced crew size configuration, however here a clear difference in command team strategy was observed. In the low demand scenarios the command team had a greater number of total interactions than the high demand scenarios. It appears that in the low demand scenarios the command team was operating within capacity and the generation of the tactical picture was driven in a bottom-up fashion (i.e. operator led). In the high demand scenarios, the operators were potentially reaching capacity, therefore total interactions dropped, with the generation of the tactical picture being driven in a top down fashion (i.e. led by higher command). This may be due to the fact that there are too many contacts for the command team to handle, leading to higher command operators to prioritise solution generation and allocation of workload more prescriptively.

The communication activity of OOW increased by the greatest amount across all scenarios in the co-location configuration, compared to baseline (see figure 3). The OOW is required to use the tactical picture generated by the command team to inform decisions regarding submarine safety and mission completion. The new configuration has allowed the OOW to communicate with more of the command team, more frequently than in baseline. It is likely that such communication occur to support understanding of the tactical picture and to deliver commands. The communication activity of most operators also increased across all scenarios in the reduced crew size configuration compared to baseline (see figure 3). However, again the greatest increases in communication activity was observed for OOW, with the largest increase observed in the high demand scenarios. This further supports the view that to cope with demand, the new configuration has facilitated a top down tactical picture generation strategy when crew size is reduced, with OOW driving picture generation. This is further evidenced by OOW having the highest centrality of all operators in the reduced crew size configuration, which was not the case during baseline (OpsO and SoC were generally higher).

Table 3 *Social network Metrics for entire network RTPD, INSO and DT scenarios baseline, co-location and Reduced Crew size*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | RTPD | |  | |  | | INSO | |  | |  | | DT | |  | |  | |
|  | 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 |
| Nodes | 9 | 9 | 9 | 9 | 7 | 7 | 9 | 9 | 9 | 9 | 7 | 7 | 9 | 9 | 9 | 9 | 7 | 7 |
| Edges | 33 | 35 | 31 | **38** | **27** | **21** | 24 | 37 | 34 | 31 | **24** | **24** | 34 | 31 | **29** | **24** | **23** | **25** |
| Density | 0.46 | 0.49 | 0.43 | 0.53 | 0.64 | 0.5 | 0.33 | 0.51 | 0.47 | 0.43 | 0.57 | 0.57 | 0.47 | 0.43 | 0.40 | 0.33 | 0.55 | 0.6 |
| Cohesion | 0.34 | 0.33 | 0.33 | **0.44** | **0.62** | **0.43** | 0.31 | 0.39 | 0.36 | 0.36 | **0.52** | **0.52** | 0.31 | 0.36 | 0.31 | **0.28** | **0.52** | **0.57** |
| Total Interactions | 514 | 704 | 828 | 1112 | 686 | 872 | 1062 | 944 | 1026 | 1144 | 1136 | 1244 | 870 | 1278 | 942 | 1462 | 1052 | 1314 |



Figure 3. Social network diagrams for RTPD, INSO and DT scenarios low and high demand, with co-location and reduced crewsize

Information network analysis

In the co-location configuration the number of total interactions between information elements is much greater during than during baseline studies across all scenario types (see table 6 and figure 4). The observed increase were generally even greater in the reduced crew size configuration. Where despite the command team size being smaller, the volume of information passed through the control room increased compared to baseline (RTPDL = 698, RTPDH = 1024, INSOL = 1865, INSOH = 204, DTL = 1192, DTH = 1945). This suggests that the new configuration increased the capacity of the command team to pass a greater volume of information and utilisation of such capacity was maximised as a coping strategy for crew size reduction in high demand. The density of all co-location information networks was higher than baseline indicating that information elements were also much more connected. However, across all scenario types only four new information elements (track, Inshore, Boat and Class) were introduced to the “top 10” from baseline studies. This suggests that whilst the command team exchanged more information in the co-location configuration, the type of information remained largely the same, suggesting that the new configuration increased the capacity for task relevant information to be communicated. The fact that pertinent information is more connected suggests also that it is being exchanged more efficiently.

In the reduced crew size configuration the density of the information differed compared to baseline, some of the differences revealed much denser networks and some less dense depending on scenario type and demand (RTPDL = 0.22, RTPDH = 0.23, INSOL = 0.17, INSOH = -0.20, DTL = -.08, DTH = 0.47). This suggests that whilst the capacity of the information networks has increased the manner in which the capacity is utilised differed depending upon the particular operation being completed and demand, suggesting more adaptive networks as a result of the new configuration. Across all scenario types only 3 new information elements (fishing, inshore and north) were introduced from the “top 10” suggesting that whilst more information was exchanged in the reduced crew size, the type of information exchanges remained operationally relevant in line with current ways of working (as with the full crew size co-location configuration).

Table 6. Global information network metrics for RTPD, INSO, and DT low and high demand scenarios in baseline co-location and reduced crew size configuration

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | RTPD | | | | | | INSO | | | | | | DT | | | | | |
|  | 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 |
| Nodes | 40 | 45 | 45 | 55 | 47 | 53 | 39 | 46 | 58 | 66 | 59 | 63 | 46 | 57 | 52 | 62 | 61 | 59 |
| Edges | 340 | 502 | 526 | 788 | 508 | 770 | 418 | 518 | 986 | 1322 | 1110 | 1108 | 644 | 920 | 998 | 998 | 992 | 1104 |
| Density | 0.41 | 0.57 | 0.57 | 0.81 | 0.63 | 0.81 | 0.87 | 0.97 | 0.90 | 0.69 | 1.04 | 0.77 | 0.95 | 0.68 | 1.11 | 0.85 | 0.87 | 1.15 |
| Cohesion | 0.21 | 0.25 | 0.27 | 0.27 | 0.23 | 0.30 | 0.28 | 0.25 | 0.30 | 0.31 | 0.32 | 0.28 | 0.31 | 0.28 | 0.37 | 0.26 | 0.27 | 0.32 |
| Total Interactions | 666 | 1196 | 1756 | 2582 | 1364 | 2220 | 1700 | 2812 | 2966 | 2974 | 3565 | 3016 | 2060 | 2080 | 2956 | 3202 | 3252 | 4025 |



Figure 4. Information networks for DT low demand co-location configuration and reduced crew size

The information elements with the highest number of emissions during baseline (e.g., ‘bearing’, ‘contact’, ‘course’ and ‘speed’) were typically amongst the highest during the co-location configuration and with a reduced crew size. With the total number of emissions remaining relatively stable (see figure 4). This suggests that the type of information that is most important to the command team has not changed as a result of the new configuration. Although the capacity of the command team to pass this type of information has increased as a result of the new configuration as the emissions of critical information from baseline has increased, particularly during the high demand scenarios. The only exception to this was in the reduced crew size configuration RTPD scenarios the concepts ‘bearing’ ‘contact’ and ‘knots’ had the highest number of emissions during baseline. Whilst the emissions of these concepts increased slightly in the reduced crew size configuration, their prevalence remained relatively stable. However, emissions of ‘course’, ‘sonar’ and ‘range’ increased by a much larger extent making these information elements the most frequent in terms of emissions. Despite this, the information with the highest centrality remained to be ‘contact’. This suggests either the command team was able to communicate more information (a pull factor effect), or they needed more information (a push factor effect), concerning the parameters of ‘contacts’ from ‘sonar’ such as their ‘course’ and ‘range’ to supplement knowledge of ‘bearing’ and ‘knots/speed’ than was the case in baseline. Knowledge of surrounding contacts is critical to submarine safety during a RTPD, as only by knowing the likely behaviour of contacts can an OOW order a RTPD in a safe area where there is no likelihood of collision.

It appears that the co-location configuration (both with a full and reduced crew size) has facilitated the communication of more detailed, mission specific information. For example, the sociometric status of ‘contact’ remained consistent in the DT high and low scenarios in the co-location configuration. However, the sociometric status and centrality of the information element ‘Nimitz’ increased by the largest amount of all information elements across all scenarios. The mission objective during the DT scenarios was to covertly track a particular ‘contact’ the ‘Nimitz’. The co-location configuration appears to have facilitated more transitions of information specifically related to ‘Nimitz’ which was the primary objective. Positioning the SoPs and TMAs together has increased the capacity of these operators to communicate more frequently; it appears the increase in communication has been task relevant, relating to the primary mission objective.

C. Task network analysis

The task networks were the same during the co-location and reduced crew size configuration as they were during baseline, as the fundamental tasks completed by the command team remained the same. This supports the proposition that the work remained identical, apart from the changes to control room configuration and crew size. Whilst the configuration change affected the flow of and type of information being utilised by the command team, the fundamental tasks being completed and the connectivity between tasks remained the same. The tasks networks for the three different operation types were relatively similar in terms of how the tasks are clustered. The primary differences relate to when a particular type of instrument or sensor is used (e.g., periscope vs. sonar) and the sequences in which tasks are completed. For example, during RTPD the periscope will only be used once at the end of the scenario once a particular depth (63 feet) has been reached, relying on sonar for the majority of the scenario. However, during an INSO scenario the periscope is routinely raised and lowered in a near continuous fashion, as the command team continuously shifts between utilising visual and sonar information to inform the tactical picture.

The frequency of task completion did change and differed depending on operation type and demand (see table 10). In general, in the co-location configuration, the total number of tasks completed during all scenarios increased, although differences in the high demand scenarios were more substantial (RTPDL = 0, RTPDH = 27, INSOL = 17, INSOH = 24, DTL = -11, DTH 31). This indicates that the new configuration improved the efficiency of the command team, allowing them to complete a much greater volume of tasks in the high demand scenarios. Having operators who are dependent on each other for task relevant information, positioned next to each other means that information that facilitates sub-task completion can be shared with greater efficiency and more frequently. An example of this is that the TMAs rely on contact speed estimates from the SoPs analysis tools to generate and refine solutions, in baseline conditions these operators were in separate rooms and this information was required to be passed via OpsO and SoC. In the co-location configuration, the SoPs and TMAs are positioned next to each other and so can directly share contact speed estimates. This allows OpsO and SoC to focus on additional command based tasks (e.g., focusing on a priority contact and quality checking work) rather than acting as an information brokers.

In the reduced crew size condition, the total number of tasks being completed by the command team decreased when compared to baseline, particularly during the DT scenarios (RTPDL = -6, RTPDH = -6, INSOL = 1, INSOH = -1, DTL = -13, DTH -15). This is not surprising, as the removal of two operators (SOP and TMA) reduced the capacity of the team to complete tasks. However, interestingly, during INSO the removal of the operators did not greatly effect the number of tasks completed. During this scenario there is a much greater reliance on periscope to provide reliable visual information to ensure submarine safety and complete mission objectives. In the DT and scenarios there is greater reliance on more ambiguous sonar information. Therefore, removal of one SOP and TMA in this instance appears to have reduced capacity. It appears that the impact a reduction in crew size has upon task completion is operation specific. This indicates that the control room design can facilitate flexible and interactive team interoperability in response to changes in operational requirements. However, overall, the reduction in frequency of task completion, even with a reduced crew size was quite small, indicating that the new co-figuration had optimised command team efficiency.

Table 10. Node metrics and frequency counts for INSO and DT baseline, co-location and reduced crew size configurations

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | | |  | | |
|  | **Baseline** | |  | | | **Co-location** | | |  | | **Reduced** | |  | |
|  | INSL | DTL | INSH | | DTH | INSL | | DTL | INSH | DTH | INSL | DTL | INSH | DTH |
| **OOW brief** | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Raise Periscope** | 3 | 5 | 3 | | 2 | 3 | | 1 | 5 | 1 | 3 | 3 | 6 | 1 |
| **1st Sweep** | 6 | 7 | 5 | | 2 | 4 | | 2 | 5 | 2 | 5 | 3 | 8 | 1 |
| **Detect Close Visual** | 7 | 8 | 5 | | 4 | 4 | | 3 | 9 | 2 | 4 | 3 | 7 | 1 |
| **Designate Visual** | 7 | 3 | 1 | | 3 | 4 | | 3 | 4 | 1 | 3 | 3 | 5 | 1 |
| **Lower Periscope** | 3 | 5 | 3 | | 2 | 3 | | 1 | 5 | 1 | 3 | 3 | 5 | 1 |
| **Classify visual** | 7 | 3 | 4 | | 1 | 5 | | 3 | 5 | 1 | 5 | 1 | 5 | 1 |
| **Range of visual** | 8 | 15 | 10 | | 6 | 14 | | 3 | 9 | 3 | 3 | 3 | 4 | 2 |
| **Visual Solutions** | 7 | 3 | 1 | | 1 | 3 | | 1 | 2 | 1 | 2 | 1 | 2 | 0 |
| **Detect contacts sonar** | 3 | 3 | 4 | | 9 | 3 | | 4 | 6 | 9 | 4 | 5 | 7 | 7 |
| **Designate sonar** | 3 | 5 | 6 | | 13 | 2 | | 5 | 4 | 9 | 3 | 2 | 6 | 7 |
| **Classify Sonar Contacts** | 1 | 5 | 6 | | 4 | 5 | | 6 | 6 | 9 | 6 | 5 | 6 | 7 |
| **Speed estimates** | 0 | 7 | 4 | | 5 | 4 | | 7 | 4 | 10 | 3 | 10 | 10 | 9 |
| **Identify sonar merges** | 0 | 0 | 0 | | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Check cuts received** | 1 | 2 | 4 | | 9 | 2 | | 7 | 8 | 12 | 1 | 0 | 3 | 5 |
| **Generate Solutions** | 1 | 4 | 7 | | 6 | 6 | | 3 | 5 | 8 | 3 | 4 | 4 | 8 |
| **Steer vessel** | 6 | 1 | 6 | | 8 | 15 | | 12 | 9 | 19 | 12 | 12 | 10 | 10 |
| **Refine solutions** | 6 | 5 | 18 | | 4 | 10 | | 9 | 7 | 19 | 10 | 10 | 6 | 3 |
| **Total tasks** | 70 | 82 | 70 | | 77 | 87 | | 71 | 94 | 108 | 71 | 69 | 89 | 62 |

In the co-location configuration RTPD scenarios the biggest differences of task frequency was observed for the generation and refinement of solutions in the high demand scenarios. The generation of solutions involves the logical assimilation of information estimated about a contact from a range of sensors (depending on depth and covertness) to predict the likely behaviour of the contact. The generation of multiple solutions leads to the building of a tactical picture, which informs the OOW where is safe to operate and where is likely to be safe to RTPD. The refining of solutions is critical, as the parameters of contacts may change (e.g., speed or course changes) and so solution accuracy may diminish. It appears that the new configuration has improved command team efficiency allowing the generation of more solutions which will ultimately improve submarine safety. In the reduced crew size condition the number of solutions generated remained relatively similar to baseline. However, the number of speed estimates generated was fewer, potentially as a direct result of having one less SOP, responsible for speed estimate generation. However, the frequency of the task steer safe course was completed a much greater number of times, particularly in high demand. This appears to be a further example of a different command team strategy being employed to cope with increased demand and fewer operators. It appears that higher command was more proactive in steering own submarine away from contacts, potentially allowing a focus on a smaller number of contacts, within capacity limitations.

Table 11. Node metrics and frequency counts for RTPD baseline, co-location and reduced crew size configurations

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Task Frequencies** | | |  |
|  | **Baseline Low** | **Baseline High** | **Co-location Low** | **Co-location High** | **Reduced Low** | **Reduced High** |
| **OOW brief** | 1 | 1 | 1 | 1 | 1 | 1 |
| **Detect contacts sonar** | 4 | 5 | 1 | 8 | 1 | 2 |
| **Designate sonar contact** | 3 | 4 | 1 | 6 | 1 | 2 |
| **Classify Sonar Contacts** | 4 | 7 | 3 | 10 | 3 | 5 |
| **Speed estimates** | 4 | 6 | 3 | 6 | 2 | 2 |
| **Sonar Courses** | 1 | 6 | 3 | 8 | 2 | 4 |
| **Identify sonar merges** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Check cuts are received** | 4 | 3 | 3 | 3 | 1 | 1 |
| **Generate Solutions** | 3 | 8 | 4 | 12 | 4 | 7 |
| **Steer safe course** | 5 | 2 | 7 | 7 | 8 | 10 |
| **Refine solutions** | 1 | 2 | 2 | 10 | 4 | 4 |
| **Clear Stern arcs** | 1 | 1 | 1 | 1 | 0 | 1 |
| **Final Reports** | 1 | 1 | 1 | 1 | 0 | 1 |
| **Raise Periscope** | 1 | 1 | 1 |  | 1 | 1 |
| **1st Sweep** | 2 | 1 | 2 | 2 | 1 | 1 |
| **Detect Close Visual** | 1 | 1 | 3 | 1 | 1 | 1 |
| **Lower Periscope** | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total** | 37 | 50 | 37 | 77 | 31 | 44 |

It does appear that the frequency of task completion was operation specific. In the co-location configuration for example, the frequency of tasks such as refining solutions decreased in the INSOH scenario compared to baseline but increased during the DTL condition (see table 10). This indicates that more tasks were not completed superfluously, because capacity allowed, as during INSO less solution refinements were completed. This may be expected as solutions generated using periscope (visually) will be more accurate than solutions generated using passive sonar and so require less refinement. The tasks relating to steering own submarine were completed more frequently in the co-location configuration across all scenarios. The OOW can order a change in course to verify solutions (i.e. using basic trigonometry for ranging) or to achieve mission objectives (i.e. navigate closer inshore) but is unlikely to do so unless there is some confidence in the tactical picture (i.e. to check against). This indicates that the OOW had more confidence in the tactical picture with the new configuration to complete more maneuverers (particularly during INSO). This pattern of task completion was also observed during the reduced crew size scenarios. Interestingly, fewer sonar designations were completed during the DT scenarios when compared to baseline. At first glance this appeared to be detrimental, however, the fact that more solutions were generated, suggests that the command team was actually functioning more efficiently. During a DT scenario the submarine can operate at depth, therefore a complete surface picture is not always necessary for safety (as a RTPD is not being completed). Instead the command team can focus on the contact of interest (i.e. the contact being tracked), which resulted in fewer overall designations, but more solutions being generated.

**Discussion**

The current work investigated how a novel control room configuration affected the functionality of an expert submarine command team from a sociotechnical system perspective (Walker, Stanton, Salmon, & Jenkins, 2009; Stanton, 2014). In comparison to a previous baseline study (see figure 1), the new configuration appeared to have distributed communication across the command team more evenly, removing existing communication bottlenecks and altering the structure of information passage and frequency of task completion (Stanton, & Roberts, 2018). Moreover, the changes in configuration appeared to facilitate effective coping with crew size reduction, a drive observed in many domains to afford economics savings (Walters, French, & Barnes, 2000; Stanton, Harris, & Starr, 2016; Salotti, Heidmann, & Suhir, 2014; Allender, 2000). However, the pattern of results was not uniform across different scenario types and different demand suggesting that the new configuration facilitated greater command team flexibility depending upon operational requirements. This suggests that optimisation of sociotechnical systems does not require a one size fits all approach but rather situation specific ways of working to maximise utilisation of technology and overall productivity (Brynjolfsson & Hitt, 2000; Devaraj, & Kohli, 2003; Roco & Bainbridge 2003; Showalter, 2005).

The volume of information passed between OpsO and SoC had reduced compared to the baseline studies, although in some case more tasks were completed (Stanton & Roberts, 2018). The operators in the sound room (SoPs) are required to process sonar information and pass this to the picture compilation operators (TMAs) in the control room, to develop a tactical picture (Loft, Bowden, Braithwaite, Morrell, Huf, & Durso, 2015; Loft, Sadler, Braithwaite, & Huf, 2015). It appears that co-locating the SOP and TMAs has resulted in these operators directly exchanging information, rather than relying on OpsO and SoC as information brokers. This is further demonstrated by the fact that an increase in communication was observed between the SoPs and TMAs (Stanton & Roberts, 2018, Stanton, 2014). Whilst it might have been expected that such increases might be larger, the co-location of operators may have facilitated a greater volume of non-verbal communications not captured in the current work (Yee, Bailenson, Urbanek, Chang, & Merget, 2007).

It is clear that the co-location configuration has facilitated the transition of more information (i.e. total interaction), with greater variety of content (i.e. more nodes), that was more directly connected (i.e. edges). The fact that the information networks were so much more cohesive appears to reflect that operators were able to pass the type of information requested, at the time it was required – rather than passing as much information as possible whenever the opportunity arose (i.e. the effect of production blocking). However, it is important that increases in communication are relevant, as ineffective communication can become the limiting factor in determining workload of the team, rather than the work itself (Salas, Burke & Samman, 2001; Carletta, Anderson & McEwen, 2000). It does appear that information increases were relevant, as the information that remained the most critical remained relatively similar to baseline, suggesting the new configuration had improved information transition (Stanton & Roberts, 2018). In addition, the number of tasks completed by the command team, even in the reduced crew condition typically remained stable or increased, suggesting improved productivity.

In the co-location configuration the activities of most operators typically increased, but despite this, the operators who were higher in command (OOW, OpsO and SoC) were the busiest. This seems to indicate that the distribution of information flow and task completion responsibilities is more even across the command team. A simple example of this is that the volume of emissions and receptions between the SoPs and TMAs with their superiors was typically more balanced (i.e. between SoP1 and SoP2) compared to baseline (Stanton & Roberts, 2018). This appears to support the notion that the baseline configuration had, engineered a loafing effect, resulting in production blocking, and lower overall productivity (Stanton, Ashleigh, Roberts & Xu, 2003; Simms & Nichols, 2014; Suleiman, & Watson, 2008). The greater cohesion and density of the social and task networks appear to indicate the new configuration has removed the information bottlenecks (e.g., between OpsO and SoC) that were reducing overall output. Research in other domains has also revealed the benefits of co-location (Stanton et al, 2003), although this is not always the case (Stanton et al, 2002). It seems that the gains a highest in problem solving domains, where there is ambiguity regarding the nature of the problem and chosen solution (Stanton et al, 2003). Simpler tasks do not always shows such gains, probably because the co-location of team members does not add much value to the task (Stanton et al, 2002).

A concern about facilitating communication between the TMAs and SoPs is whether the quality checking and supervisory processes completed by OpsO and SoC were being completed as inadequate supervision is also a condition that creates social loafing (Simms & Nichols, 2014; Stanton, Connelly, Prichard and van Vugt, 2002; Suleiman, & Watson, 2008). However, the volume of communications between the operators (TMAs and SoPs) and their superiors (OpsO and SoC respectively) was generally maintained or even increased in the co-location configuration. Suggesting the senior operators could focus communications relevant to supervisory processes (e.g., prioritisation of contacts and delegation of workload) rather than simply acting as information brokers. This is supported by the fact that the type of sub-tasks that were completed more frequently typically related to tasks resulting from supervision such as refinement of solutions, which would occur as a result of initial solutions being quality checked and deemed not to be adequate (Roberts & Stanton, 2018). Moreover, the type of tasks completed more frequently were generally more related to the particular operation being completed. This suggests that the co-location configuration has facilitated the command team to be more adaptive with regard to information transition and task completion, focusing upon the completion of sub-tasks that are pertinent to a particular operation rather than a standardised, one size fits all approach to information exchange and task completion (Salas, Burke, & Samman, 2001). This was even observable in the differences observed with regard to differences in the frequency that pertinent information was passed. For example, in the DT scenarios the information node ‘Nimitz’ had much higher sociometric status in the co-location configuration, even with a reduced crew. The Nimitz was the contact that was required to be tracked, therefore a focus on information central to this contact indicates an increase in task relevant information exchange between the command team.

In the reduced crew condition it appears that a change in command team strategy occurred, particularly when comparing the high and low demand scenarios to baseline (Stanton & Roberts, 2018). During the low demand scenarios a greater number of operators directly communicated more frequently, with the tactical picture seemingly being generated in an organic bottom up fashion. This likely to be due to the fact that in the low demand conditions there were only a handful of contacts, which could be managed by a single TMA and SOP. However, in the high demand scenarios the number of contacts exceeded capacity (i.e. in RTPDH 12 contacts were presented), which resulted in the picture being driven in a top down fashion by higher command (i.e. OOW, OpsO and SoC), to prioritise workload. This is supported by the observation that OpsO and OOW communications are considerably higher during the high demand reduced crew size scenarios. This appears to reveal that the new configuration has led to different communication strategies depending upon operational requirements and demand (Stanton, Rothrock, Harvey, & Sorensen, 2015a, b; Houghton, Baber, McMaster, Stanton, Salmon, Stewart, & Walker, 2006). There is also a shift in the type of tasks most frequently performed, changes to own submarine parameters are performed more frequently, which may reflect a greater confidence in the tactical picture but may also represent the command team attempting to reduce workload (i.e. steer away from clusters of contacts if it is not possible to process everything). In the reduced crew size DTH scenarios, far fewer contacts were designated on sonar but more speed estimates and solutions were generated, suggesting the command team was in fact attempting to focus the development of the tactical picture on a smaller volume of contacts to reduce workload. It appears that this process has been facilitated by the co-location configuration, as information can be shared between task dependant operators more efficiently.

There are some limitations associated with these studies that need to be addressed. Firstly there was only one team, albeit expert serving submariners who work together operationally. Ideally, one would prefer multiple expert teams to participate so that the intra-team differences can be explored. The availability of expert submariner teams is extremely restricted, due to operational demands. Nevertheless, there is a traditional of single case studies in ergonomics research (Hancock et al, 2009). Secondly, the studies are based on the simulation of the control room rather than a real control room. It is possible that some nuances of operational control rooms might be missed but access to the real environment is be exceedingly difficult due to operational demands and access limitations. Previous research has shown that the data from control simulator to be similar to those from a Royal Navy submarine team training simulator (Stanton, 2014) and the University of Southampton simulator has been verified by subject matter experts (Stanton and Roberts, 2018). Thirdly, it should be noted that due to only one team participating, no statistical inferences were possible and all the interpretations are based on pure descriptive numerical comparisons. Arguably, social network metrics are ideally suited to single case study work, as they support such comparisons. Finally, there is the possibility of an order effect, as the baseline study was undertaken first, albeit many months before the co-location and reduced crew studies (as reported by Stanton and Roberts, 2018).

**Conclusions and future work**

The implementation of recommendations in the current work, such as co-location of TMAs and SoPs requires further evaluation of technologies to facilitate this, (e.g., noise cancelling headphones to reduce ambient noise when aural processing of data is required). Furthermore, examination of wider implications of co-location need to be investigated. In the current work for example, it is clear that during the INSO scenarios co-location configuration (including reduced crew size) the activities of Peri was greatly reduced. This may be due to the fact that the transition of information between the SoPs and TMAs, alongside the availability of OpsO and SoC to support the data integration process has optimised the use of periscope. Nevertheless, it may also reflect that the new configuration has made the integration of visual and sonar data more difficult, potentially due to the location of Peri in the new configuration. The volume of visual information and number of visual tasks being completed greatly increased, seems to support this view. Potential negative effects of co-location need to be investigated further, such as the distraction of a noisier work environment, which may be negated by the utilisation of additional technologies (e.g., noise cancelling headphones). 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.

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