



Block off: an examination of new control room configurations and reduced crew sizes examining engineered production blocking

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Abstract

Previous research has shown a potential bottleneck of communication of information between the sonar controller (SOC) and operations officer (OPSO) in submarine sound and control rooms. This research aimed to see if this bottleneck could be removed by co-locating the sound and control room teams. Further, it also looked at the effects of reducing the crew numbers. Ten teams performed the return to periscope depth tasks during high and low demand in a simulated submarine control room. Activities and communications of the teams were recorded and compared with data from a baseline condition of contemporary operations. The findings show that the co-location of the sound room and control room teams relieved the bottleneck of communications between the SOC and OPSO. Although communications increased, this was more balanced across team members and more relative to operational demand. This was coupled with more efficient task completion, resulting in greater number of tasks being completed by the command teams. Reduced crewing led to greater communications between the remaining members of the team together with task shedding in the higher demand condition. Future research should contrast these findings with objective measures of task performance to better understand potential performance benefits.

Keywords Submarine · Team work · Communications · Networks · Reduced crew

1 Introduction

The digital revolution has seen advancements in technology, computing processing capacity and sensor capabilities that is changing ways of working across many domains (Brynjolfsson and McAfee 2011). In the submarine domain, research has sought to develop new software algorithms and architectures to make the tracking of contacts by submarines more efficient and accurate (Shar and Li 2000; Wang et al. 2011; Lim 2012). In almost every domain, there is a drive to maximise productivity and reduce economic cost (Ireland and Schuh 2008; Brynjolfsson and Hitt 2000; Devaraj and Kohli 2003; Huddleston and Harris 2017; Schutte 2017). This relies on the interaction of human operators and technology, with growing interdependence in pursuit of purposeful, goal-directed behaviours—the definition of a sociotechnical system (Walker et al. 2009). However, new technology is frequently installed without adequate consideration of how

to obtain maximal utility from an upgrade from a sociotechnical perspective (Hamburger et al. 2011; Mankins 2009). Adopting a sociotechnical systems approach appreciates the complexities involved with systems and how their design can be improved (Stanton 2014; Stanton and Roberts 2017; Roberts and Stanton 2018; Klein et al. 2003).

The continuing advancement of technology means that sociotechnical systems will further transform ways of working to increase capability (Roco and Bainbridge 2003; Showalter 2005). This is evident across many domains including aircrafts (Rudisill 2000; Bruce et al. 1998; Stanton et al. 2016), surface vessels (Lützhöft and Dekker 2002; Negahdaripour and Firoozfam 2006) and gas/electric/nuclear power plants (Santos et al. 2008; Stanton et al. 2010). The requirements for future submarine platforms will be guided by advancements in technology, operational capability and economic constraints. This will likely include new instruments (e.g. unmanned underwater vehicles—UUVs), improved sensor capacity (e.g. higher fidelity sonar arrays), advancements in control room design and maintenance/reduction of staffing requirements (Hewish 2002). It is critical that such advancement includes evaluation of new technologies and ways of working from a sociotechnical systems

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perspective (Hamburger et al. 2011; Stanton and Roberts 2017; Stanton et al. 2017).

2 Social loafing

A critical challenge in team environments is creating conditions where knowledge can effectively be shared between individuals to generate knowledge at the level of the team to support higher order objectives (Fiore et al. 2018; Roberts and Stanton 2018). It is important to understand cognition in the minds of individual operators, but also to examine cognition between the minds of individuals, the processes affording macrocognition (Klein et al. 2006; Cooke et al. 2008). Such processes are often supported by technologies to facilitate interdependence between operators (Stanton et al. 2010; Zhang and Patel 2006). However, such technologies can also have a negative impact upon team processes. Social loafing for example, increases in technology-supported and location distributed teams, with the potential for overall productivity loss (Simms and Nichols 2014; Suleiman and Watson 2008; Stanton et al. 2003). Social loafing refers to instances where individuals working in a group exert less effort than when working alone (Simms and Nichols 2014). The factors promoting social loafing are debated, but include individual accountability, uniqueness of operator, group size, supervisory input, fatigue and task difficulty (Simms and Nichols 2014; Suleiman and Watson 2008; Alnuaimi et al. 2010).

In many domains the drive to reduce economic costs of sociotechnical systems have been achieved by reducing crew size (Walters et al. 2000; Stanton et al. 2016; Salotti et al. 2014). The economic savings associated with reduced crew sizes can be substantial (Allender 2000) and in certain situations have been demonstrated to improve efficiency (Watkins et al. 2009). However, a primary consideration is the impact a reduction in crew size has upon team performance and operational safety (Salotti et al. 2014). It is suggested that larger team sizes can be detrimental to global task performance as conditions for social loafing are increased, with not all team members contributing maximally to global team objectives (Alnuaimi et al. 2010). An investigation of crew size therefore is not necessarily concerned with a manning reduction, but whether command team capacity is being optimally utilised.

3 Engineering change

The configuration of submarine control rooms has not changed greatly across a century of operations (Stanton 2014). The original designs were constrained by engineering principles such as the use of hull penetrating periscopes, and particular hull compositions requiring the control room

to be positioned in a small space at the top of the submarine (Binns 2008; Burcher and Rydill 1995). A large number of such restrictions have been removed by engineering advancements, such as the introduction of non-hull penetrating optronics masts (Pratt 1988; Duryea et al. 2008). Furthermore, the historical requirement for a separate sound room area to reduce ambient noise when processing aural data, is no longer a necessity with the development of noise cancelling technologies and waterfall displays (Arrabito et al. 2005). Technological advancements such as these pave the way for new thinking in terms of control room design.

A previous study by Stanton et al. (2017) examined submarine command teams contemporary ways of working during a return to periscope depth (RTPD). It was found that command teams typically increase communications during situations of high demand, demonstrate a reliance on certain operators within the command team as information brokers and promote a dearth of direct communication between operators highly dependent on each other for task-relevant information. Pertinent examples of this included a bottleneck of information transition observed between the sonar controller (SOC) and the operations officer (OPSO), who provide the only direct link between the sound and picture rooms (Stanton 2014; Stanton and Roberts 2017; Roberts and Stanton 2018). Also, the target motion analysis operators (TMA)s rely on information from the sonar operators (SOP)s to integrate with visual data when generating contact solutions (Loft et al. 2015a, b). Yet the communication between these operators was amongst the lowest in the control room during a RTPD (Stanton et al. 2017).

A critical question concerns whether the design of the sociotechnical system itself causes a reduction in productivity, in the form of unintentionally engineered production blocking and/or social loafing (Stanton et al. 2003). The configuration of a team and the way in which technology supports communication can greatly influence the effectiveness of overall team performance (Stanton et al. 2015a), particularly as the number of communications that can occur between operators is finite (Roberts and Cole 2018). It is therefore important to consider if the configuration of contemporary control room designs optimises the relationship between operators and technology. Communication is critical for the attainment of team awareness, as such processes can be the determining factor in terms of team workload rather than the work itself (Stanton 2011; Salas et al. 2001; Carletta et al. 2000).

In the current work, two studies examined the impact a novel control room configuration had upon submarine command team performance; with two different crew sizes during high and low -demand RTPD scenarios. This builds on a previous study that examined current ways of working during RTPD scenarios, which was used as a baseline comparator (Stanton et al. 2017).

4 Method

The current study builds upon previous work examining the performance of submarine command teams in a control room configuration based upon the currently operational Astute class submarine (baseline). An in-depth investigation of the baseline studies has been completed (Stanton et al. 2017). The aim of the current study is firstly to evaluate the co-location configuration and reduced crew size condition in isolation and secondly to compare these results directly to the baseline configuration.

5 Participants

A total of 150 participants, 130 males and 20 females with an age range of 18–55 (mean 27.89, SD 7.86), were recruited opportunistically using posters and by directly contacting organisations with a military interest; participation was voluntary. Use of novice teams was justified by the fact that relative, rather than absolute, differences between conditions (and direction of those effects) were of most interest (Walker et al. 2010a, b). Participants were randomly allocated to one condition based on time of recruitment (baseline studies were run first). Ten teams of eight individuals, 71 males and 9 females with an age range of 18–55 (mean 26.83, SD 8.69), were recruited for the baseline study. In the co-location configuration (study one) 59 males and 11 females participated (in ten teams of seven) with an age range of 20–48 (mean 28.94, SD 7.02). The same (as study one) cohort of participants were used in the reduced crew size condition (study two) but two operators were removed from the team, with a total of 44 males and six females (ten teams of five) remaining with an age range of 20–48 (mean

28.98, SD 7.28). One team in baseline and one team for both study one and two were submariners from the British Royal navy (RN). Ethical approval was received from the University of Southampton Research Ethics Committee (Protocol No: 10099) and MoDREC (Protocol No: 551/MODREC/14).

6 Equipment: the submarine control room simulator

A submarine control room simulator was built to be representative of a currently operational RN submarine (for fuller description see Roberts et al. 2015, see Fig. 1a for configuration). The control room had nine networked workstations which had the simulation engine dangerous waters (DW) installed. This featured networked workstations for each of the operator roles included in the simulator. The roles chosen for inclusion in the control room were informed by subject matter experts (SME) and 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). In all studies the role of the OOW was assumed by an experimenter in order to guide the scenarios tactically. In study one, the configuration of the control room was changed (see Fig. 1b) based upon the findings of baseline studies and input from human factors and SMEs and submarine operation SMEs. The only change made was to the configuration of the control room, all other aspects remained the same to avoid experimental confounds.

Two RTPD scenarios were designed with SME input and programmed in DW (see Table 1). Each scenario lasted approximately 45 min and the movements of contacts were predetermined to be consistent across all teams. The simulator was equipped with suite of recording devices such as web

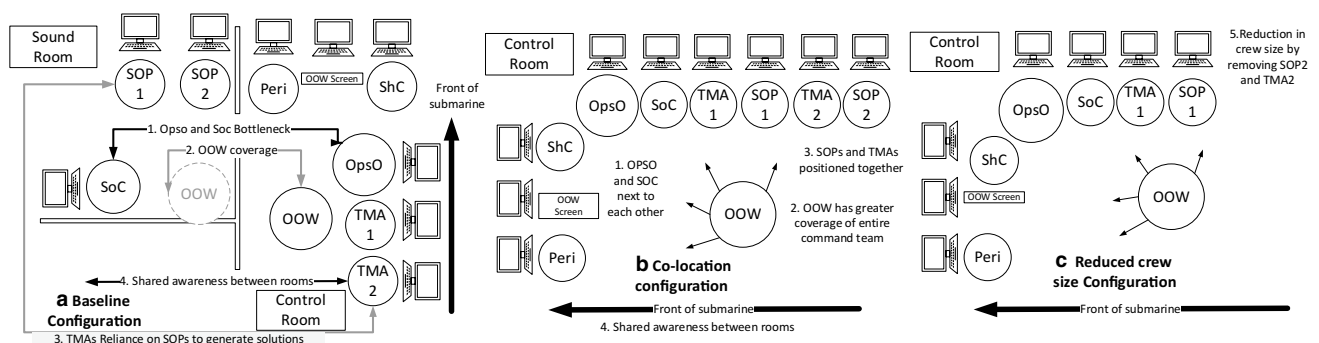


Fig. 1 Control room configurations. **a** Is the baseline configuration. The critical issues that required addressing based upon SME recommendations included: (1) the bottleneck in communications between OPSO and SOC, (2) OOW being required to supervise two separate rooms, (3) TMAs and SOPs being highly 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. **b** Is the novel configuration proposed by the SME panel to be investigated. **c** Is the co-location configuration with a reduced crew size (SOP1 and TMA1 removed)

Table 1 Description of scenarios designed

Name	Demand	No. contacts	Mission
Return to periscope depth (RTPD)	Low	4—fishing	RTPD from deep to send intelligence home, large temporal window of opportunity. All contacts held must be ranged to find optimum course for RTPD. Scenario complete once periscope has marked all contacts
	High	9—fishing 3—catamaran 1—biological	RTPD as quickly as possible due to submarine damage. Attempt to range all contacts to find optimum RTPD course

cameras and ambient microphone which allowed the recording of all communications that occurred between operatives.

7 Design

The co-location configuration was examined independently using a 2×9 mixed design (social networks), a 2×14 repeated measures design (information networks) and a 2×12 repeated measures design (task networks). The design of study two was identical to study one, except a 2×7 mixed design was employed for the social networks when investigating the reduced crew size in isolation. The independent variables were scenario demand (within subjects), operator role (between subjects—social network), information type (within subjects—information network) and task type (within subjects—task network). Scenario demand was manipulated by the number of contacts detectable in the scenario, contact behaviour (e.g. speed and course changes vs. steady) and area of operation (see Table 1). The design of scenarios was informed by SMEs to be representative of real high and low-demand RTPD operations. The dependent variables were static adjacency matrices (social, information and task) derived from the communications that took place between operators within the command team.

The co-location configuration and reduced crew size condition were then compared to baseline, extended the study design employing a $2 \times 2 \times 9$ mixed design (social networks), a $2 \times 2 \times 14$ mixed design (information networks) and a $2 \times 2 \times 12$ repeated measures design (task networks). For the reduced crew size configuration a $2 \times 2 \times 7$ mixed design was used to compare the reduced crew to baseline. The comparison of the configurations was between subjects.

8 Procedure

The procedure used was identical for all conditions, and the training and testing protocol remained the same. Participants attended the submarine simulator for two full days in baseline studies, and three full days for the co-location and reduced crew size studies (8 am–5 pm). Informed consent was obtained on the first day prior to a simulation induction and

random assignment of team roles. On the first day (training) the morning was spent watching a set of general submarine control room operation tutorials, and in the afternoon participants watched workstation specific tutorials and practiced tasks both individually and as a functional command team. Regular breaks and refreshments were provided between tutorials, with each tutorial lasting approximately 45 min.

Participants started the second day (testing) with a refresher training scenario as a functional command team. During the refresher scenario, performance was assessed by experimenters to check that all tasks were being completed accurately in line with set criteria provided by SMEs (e.g. adequately detecting surrounding vessels and gaining solutions concerning surrounding vessels). After this the first scenario was begun—all recording devices were started and a verbal time stamp was read aloud for synchronisation purposes. At the start of each scenario the OOW gave a briefing outlining the mission objectives (see Table 1). When this mission objective had been achieved the end of the scenario was called and participants were given a short break before the start of the next scenario. Scenario presentation was counterbalanced across the 20 teams in order to reduce order effects. Each team completed both scenarios and participants occupied the same positions in the command team for both. At the end of the final scenario participants were provided with a full debrief and thanked for participating. Participants in the co-location configuration and reduced crew size condition attended for a third day, which followed the same procedure, without the refresher training scenario. To prevent practice effects the order of participation (study one vs. study two) was also counterbalanced.

9 Analysis of data

A new shortened version of Event Analysis for Systemic Teamwork (EAST: Stanton et al. 2008) was used to analyse the data. EAST examines complex sociotechnical systems using a network approach. This method has been presented in a previous study to model submarine command and control (Stanton 2014) and was used in the baseline study (Stanton et al. 2017). The framework has also been applied in other domains such as emergency services

(Houghton et al. 2006), road safety (Salmon et al. 2014), air traffic control (Walker et al. 2010a) aviation (Stewart et al. 2008) and military risk assessment (Stanton and Harvey 2017). EAST facilitates an understanding of the processes undertaken by a submarine command team having completed an RTPD, utilising a network approach to understand how people, technology, information and tasks were connected. Firstly, social networks analyse communications taking place between ‘agents’ in the system. Secondly, the information networks describe information nodes or ‘elements’ that different agents in the system use and communicate during task performance. Finally, task networks describe the relationships between tasks, their sequence and interdependences.

The social, information and task networked were generated from the raw data from video and microphone recordings. The top 14 information elements (according to frequency count) were included in the statistical analysis of the information nodes. The information nodes were determined using Leximancer software (version 2.1), a software program for identifying concepts in text documents. Networks were processed using AGNA software (version 2.1.1—a software program for computing social network metrics). AGNA was also used to compute whole network metrics and nodal metrics (for definitions see Table 2).

The analysis of data was completed in two stages. Firstly, each experimental condition was examined independently. For the co-location configuration, the effect of scenario demand on global network metrics (for social and information networks) was examined using dependent *t* tests. A 2×9 (demand \times operators) mixed analyses of variances (ANOVAs) were conducted to examine the effect of scenario demand and operator role. The effect of scenario demand on information node metrics was examined using 2×14 (demand \times information nodes) repeated measures ANOVAs. 2×12 (demand \times task nodes) repeated measures ANOVAs were conducted to examine differences in the frequency of task completion between scenarios of high and low demand. The statistical analysis for the reduced crew size (study 2) was almost identical, except a 2×7 (demand \times operators) mixed ANOVAs was used to examine individual nodes

when looking at the reduced crew size independently. In the interests of completeness, the statistical analysis of the baseline tests were reported in the tables, however the results were not discussed in more detail as they are reported in the baseline studies and are outside of the scope of the current work. All other significant main effects were examined by conducting post hoc pairwise comparisons. To account for multiple comparisons the Bonferroni correction method was used ($\alpha = 0.05/\text{number of comparisons}$).

Secondly, a comparison of the co-location to the baseline configuration was examined. 2×2 mixed ANOVAs were conducted to examine the effect of configuration and scenario demand on global network metrics (for social and information networks). The effect of configuration, scenario demand and operator role on social node metrics was examined using $2 \times 2 \times 9$ (manipulation \times demand \times operators) mixed ANOVAs. To examine the effect of configuration and scenario demand on information node metrics $2 \times 2 \times 14$ (manipulation \times demand \times information nodes) mixed ANOVAs were conducted. Differences in the frequency of task completion based upon configuration and demand were examined using $2 \times 2 \times 12$ (manipulation \times demand \times task nodes) repeated measures ANOVAs. The statistical analysis for the reduced crew size comparison to baseline was almost identical, except a $2 \times 2 \times 7$ mixed ANOVAs were conducted to examine individual social nodes in the social network between baseline and the reduced crew size. When reporting the results of the configurations comparison main effects of demand were not reported, instead the interactions between demand and manipulation was focused upon, as this was the primary interest of the current work. All statistical analysis was conducted using IBM SPSS v21.

10 Results for co-location configuration

10.1 Social network analysis

In the co-location configuration the average frequency of communications between operators in the command team

Table 2 Definitions of global network metrics and node metrics

Metric	Definition
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
Emission	Number of links emanating from node in the network
Reception	Number of links emanating going to each node in the network
Sociometric	Number of emissions and receptions relative to the number of nodes in the network
Centrality	Extent to which network revolves around a single node

varied depending on command team role and scenario demand (see Fig. 2—key nodes highlighted in black). The overall composition of both networks is similar, however the volume of interactions between operators increased during the high demand co-location RTPD scenarios.

10.2 Whole network metrics

The number of edges ($t_9 = -3.42$, $p < 0.05$, $r = 0.75$), density ($t_9 = -3.62$, $p < 0.05$, $r = 0.77$) and total interactions ($t_9 = -9.15$, $p < 0.05$, $r = 0.95$) statistically significantly increased in the high demand co-location condition when compared to low demand. The total number of edges ($F_{1,18} = 5.57$, $p < 0.05$, $\eta_p^2 = 0.24$), density ($F_{1,18} = 4.98$, $p < 0.05$, $\eta_p^2 = 0.22$), and cohesion ($F_{1,18} = 33.24$, $p < 0.01$, $\eta_p^2 = 0.65$) of the entire networks were statistically significantly affected by configuration type. This indicates that the structure of the social networks fundamentally changed as a result of the new configuration (see Fig. 2; Table 3).

11 Nodal metrics

11.1 Emissions

In the co-location configuration the total emissions of each node were statistically significantly affected by scenario demand ($F_{1,81} = 303.64$, $p < 0.01$, $\eta_p^2 = 0.79$) and operator role ($F_{8,81} = 66.23$, $p < 0.01$, $\eta_p^2 = 0.87$). The interaction of scenario demand and role also statistically significantly affected total node emissions ($F_{8,81} = 18.24$, $p < 0.01$, $\eta_p^2 = 0.64$). When examining the effect of scenario demand, post hoc analysis revealed that overall, emissions were statistically significantly higher ($p < 0.05$) in the high demand RTPD condition than the low-demand condition. All operators except PERI and SHC had statistically ($p < 0.05$) higher emissions in the high demand condition than the low-demand condition. When examining the effect of role post hoc analysis revealed that OPSO had statistically significantly higher ($p < 0.05$) emissions than all other operators (see Table 4; Fig. 2). OOW and SOC had statistically significantly ($p < 0.05$) more emissions than all operators except

Fig. 2 Social network diagrams for low and high demand co-location RTPD scenarios. OPSO had the largest volume of emissions and receptions of all operators. Overall, communications between operators were more evenly distributed when compared to baseline. In particular the bottleneck between OPSO and SOC (highlighted in black) had been reduced and communications between the SOPs and TMAs (highlighted in grey) were greatly increased

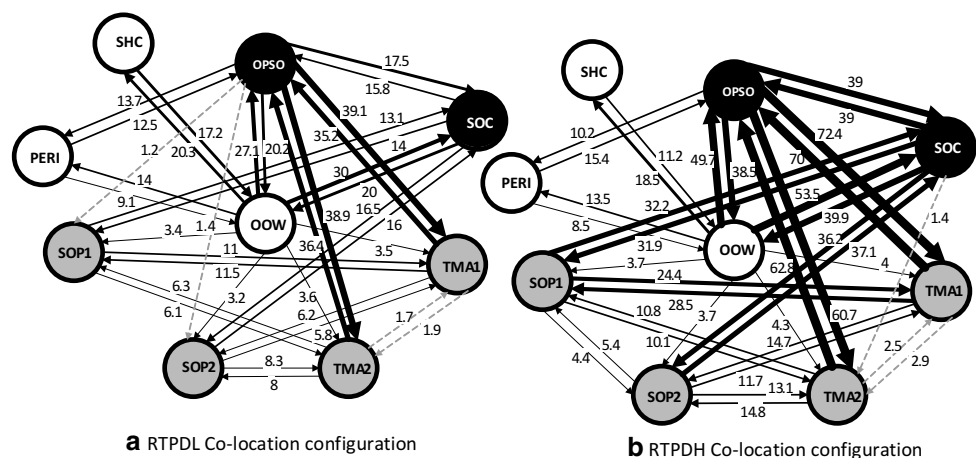


Table 3 Social network metrics for whole network RTPD baseline and co-location configuration

	RTPD				Effect of demand co-location configuration	Effect of configuration
	Baseline configuration		Co-location configuration			
	Low	High	Low	High		
Edges	36.80 ± 3.01	36.50 ± 4.93	32.90 ± 1.97	35.60 ± 2.07	3.42*	5.57*
Density	0.51 ± 0.04	0.51 ± 0.07	0.46 ± 0.03	0.50 ± 0.03	3.61*	4.98*
Cohesion	0.34 ± 0.03	0.35 ± 0.03	0.40 ± 0.04	0.42 ± 0.02	1.72	33.23***
Total interactions	663.80 ± 206.32	816.10 ± 221.10	511.70 ± 72.88	904.10 ± 169.81	9.15***	0.28

* $p < 0.05$

*** $p < 0.001$

Table 4 Social network metrics for individual nodes RTPD low and high demand scenarios for baseline and co-location configuration

	Emission				Reception			
	Baseline		Co-location		Baseline		Co-location	
	Low	High	Low	High	Low	High	Low	High
OOW	111.2 ± 32.44	117 ± 45.6	105.1 ± 10.32	150.9 ± 30.19	83.2 ± 30.5	94.5 ± 40.46	67 ± 7.67	102.5 ± 17.15
OPSO	158.2 ± 55.27	204.2 ± 52.97	132 ± 25.13	222 ± 41.19	161.7 ± 43.21	204.7 ± 49.82	127.2 ± 22.83	233.1 ± 38.96
SOC	141 ± 46.39	193.2 ± 54.35	66.3 ± 11.35	149.1 ± 32.99	143.8 ± 42.81	191.8 ± 50.93	76.6 ± 16.57	162.8 ± 40.05
SOP1	59.2 ± 34.98	64.5 ± 35.02	30.9 ± 10.97	71.3 ± 33.7	55.2 ± 34.14	72.9 ± 43.04	37 ± 12.31	81 ± 34.52
SOP2	50.8 ± 25.26	72.1 ± 39.64	31 ± 21.47	67.5 ± 30.7	58.1 ± 29.8	71.1 ± 36.68	35.9 ± 17.31	74.6 ± 25.64
TMA1	36.9 ± 16.66	61.8 ± 23.19	55 ± 20.36	116.4 ± 30.02	52.7 ± 20.5	70.8 ± 18.82	61.1 ± 20.22	115.7 ± 26.36
TMA2	49.5 ± 17.83	58.1 ± 20.18	52.6 ± 20.32	91.8 ± 30.82	58.3 ± 19.99	68.4 ± 28.76	58.8 ± 16.34	92.4 ± 26.66
PERI	33.7 ± 9.19	25.8 ± 17.19	22.4 ± 3.69	20.9 ± 4.86	26.7 ± 7.32	20.9 ± 14.56	28.6 ± 4.01	24.7 ± 5.62
SHC	23.3 ± 13.59	19.4 ± 10.15	16.4 ± 4.48	14.2 ± 5.16	24.1 ± 9.89	21 ± 7.72	19.5 ± 4.62	17.5 ± 5.78
Demand co-location	19.94***		303.64***		21.49***		342.92***	
Role co-location	40.41***		66.23***		42.87***		67.02***	
Demand × role co-location	3.43***		18.24***		2.77***		25.86***	
Configuration	0.91				1.01			
Configuration × role	5.63***				3.60**			
Configuration × role × demand	1.24				2.08*			
Sociometric								
	Baseline		Co-location		Baseline		Co-location	
	Low	High	Low	High	Low	High	Low	High
OOW	24.3 ± 7.46	26.44 ± 10.72	21.52 ± 2.1	31.68 ± 5.84	5.61 ± 0.35	5.77 ± 0.35	5.96 ± 0.21	5.74 ± 0.16
OPSO	39.99 ± 11.14	51.11 ± 12.52	32.4 ± 5.78	56.93 ± 9.79	5.4 ± 0.3	5.31 ± 0.24	5.46 ± 0.26	5.4 ± 0.29
SOC	35.6 ± 10.99	48.13 ± 12.91	17.86 ± 3.37	38.99 ± 8.8	5.78 ± 0.5	5.68 ± 0.22	4.86 ± 0.13	4.97 ± 0.23
SOP1	14.3 ± 7.58	17.18 ± 9.65	8.49 ± 2.78	19.04 ± 8.5	4.12 ± 0.34	4.12 ± 0.14	4.29 ± 0.27	4.49 ± 0.25
SOP2	13.61 ± 6.8	17.9 ± 9.49	8.36 ± 4.82	17.77 ± 6.9	4.02 ± 0.21	4.11 ± 0.19	4.46 ± 0.33	4.42 ± 0.25
TMA1	11.2 ± 4.46	16.58 ± 4.81	14.52 ± 5.01	29.02 ± 6.74	3.91 ± 0.25	3.88 ± 0.15	4.57 ± 0.25	4.69 ± 0.2
TMA2	13.48 ± 4.58	15.82 ± 5.79	13.93 ± 4.48	23.04 ± 7.1	3.86 ± 0.11	4.01 ± 0.31	4.48 ± 0.19	4.65 ± 0.23
PERI	7.55 ± 1.71	5.84 ± 3.85	6.38 ± 0.95	5.7 ± 1.26	4.94 ± 0.47	5.07 ± 0.7	3.88 ± 0.14	3.77 ± 0.19
SHC	5.93 ± 2.87	5.05 ± 2.17	4.49 ± 1.1	3.97 ± 1.35	4.05 ± 0.31	3.79 ± 0.12	3.55 ± 0.27	3.42 ± 0.16
Demand co-location	22.86***		343.97***		0.01		0.1	
Role co-location	44.29***		68.38***		39.41***		165.17***	
Demand × role co-location	3.35***		23.03***		0.88		2.73*	
Configuration	1.02				0.47			
Configuration × role	4.78***				55.84***			
Configuration × role × demand	1.62 [†]				1.29			

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

OPSO. PERI and SHC had statistically significantly ($p < 0.05$) less emissions than all operators. When examining the interaction between demand and role post hoc analysis revealed that OOW had statistically significantly ($p < 0.05$) more emissions than SOC in the low-demand condition but not in the high demand condition. SOP1 and SOP2 had statistically significantly ($p < 0.05$) higher emissions than SHC and PERI in the high demand condition but no significant differences were observed in the low-demand condition.

The total emissions of each node were not statistically significantly affected by configuration type ($F_{1,162} = 0.91$, $p > 0.05$). The interaction of configuration type and role statistically significantly affected total emissions ($F_{8,162} = 5.63$, $p < 0.01$, $\eta_p^2 = 0.22$). The interaction of configuration type, role and demand did not statistically significantly affect emissions ($F_{8,162} = 1.24$, $p > 0.05$). Post hoc analysis revealed SOC, SHC and PERI had statistically significantly ($p < 0.05$) less emissions in the co-location configuration than baseline. TMA1, TMA2 had statistically significantly ($p < 0.05$) more emissions in the co-location configuration compared to baseline.

11.2 Receptions

In the co-location configuration the total receptions of each node were significantly affected by scenario demand ($F_{1,81} = 342.92$, $p < 0.01$, $\eta_p^2 = 0.81$) and operator role ($F_{8,81} = 67.22$, $p < 0.01$, $\eta_p^2 = 0.87$). The interaction of scenario demand and role also statistically significantly affected total node receptions ($F_{8,81} = 25.89$, $p < 0.01$, $\eta_p^2 = 0.72$). When examining the effect of scenario demand, post hoc analysis revealed overall, receptions were statistically significantly higher ($p < 0.05$) in the high demand RTPD condition than the low-demand condition. When examining the effect of role post hoc analysis revealed that OPSO had statistically significantly higher ($p < 0.05$) receptions than all other operators (see Table 4; Fig. 2). SOC had statistically significantly ($p < 0.05$) more receptions than all operators (except OPSO). All operators had statistically significantly ($p < 0.05$) more receptions than SHC and PERI. When examining the interaction of demand and role post hoc analysis revealed SOC had statistically significantly ($p < 0.05$) more receptions than OOW, TMA1 and TMA2 in the high demand condition but no significant difference between these operators was observed in the low-demand condition. OOW had statistically significantly more receptions than SOP1 and SOP2 in the low demand condition, but no significant difference was observed in the high demand condition. TMA1 and TMA2 had statistically significantly ($p < 0.05$) more receptions than SOP1 and SOP2 in the low-demand condition but no significant differences were observed in the high demand condition.

The total receptions of each node were not statistically significantly affected by configuration type ($F_{1,162} = 1.01$, $p > 0.05$). The interaction of configuration type and role statistically significantly affected total receptions ($F_{8,162} = 3.60$, $p < 0.05$, $\eta_p^2 = 0.15$). The interaction of configuration type, role and demand statistically significantly affected receptions ($F_{8,162} = 2.08$, $p < 0.05$, $\eta_p^2 = 0.15$). Post hoc analysis revealed SOC had statistically significantly ($p < 0.05$) less receptions in the co-location configuration than baseline. TMA1 had statistically significantly ($p < 0.05$) more receptions in the co-location configuration compared to baseline. No significant differences in receptions between baseline and the co-location configuration were observed for OOW, OPSO, TMA2, SOP1, SOP2, SHC or PERI. Further analysis revealed that OPSO had statistically significantly ($p < 0.05$) fewer receptions in the co-location configuration lowdemand conditions than in baseline low demand configuration.

11.3 Sociometric status

In the co-location configuration the sociometric status of each node was significantly affected by scenario demand ($F_{1,81} = 343.97$, $p < 0.01$, $\eta_p^2 = 0.81$) and operator role ($F_{8,81} = 68.38$, $p < 0.01$, $\eta_p^2 = 0.87$). The interaction of scenario demand and role also statistically significantly affected sociometric status ($F_{8,81} = 23.04$, $p < 0.01$, $\eta_p^2 = 0.70$). When examining the effect of scenario demand, post hoc analysis revealed overall, sociometric status was statistically significantly higher ($p < 0.05$) in the higher demand RTPD condition than the low-demand condition. All operators except PERI and SHC had statistically significantly higher sociometric status in the high demand condition than the low-demand condition. When examining the effect of operator role post hoc analysis revealed OPSO had statistically significantly ($p < 0.05$) higher sociometric status than all other operators. OOW, SOC and TMA1 had statistically significantly ($p < 0.05$) higher sociometric status than all operators (except OPSO). When examining the interaction of demand and role post hoc analysis revealed TMA1 and TMA2 had statistically significantly ($p < 0.05$) higher sociometric status than SOP1 and SOP2 in the low demand condition but no significant difference was observed in the high demand condition.

The sociometric status of each node was not statistically significantly affected by configuration type ($F_{1,162} = 1.02$, $p > 0.05$) or the interaction of configuration type, role and demand, although a non-significant trend was observed ($F_{8,162} = 1.78$, $p = .99$). The interaction of configuration type and role statistically significantly affected sociometric status ($F_{8,162} = 4.78$, $p < 0.01$, $\eta_p^2 = 0.19$). Post hoc analysis revealed SOC and SHC had statistically significantly ($p < 0.05$) lower

sociometric status in the co-location configuration than in the baseline condition. TMA1 and TMA2 had statistically significantly ($p < 0.05$) higher sociometric status in the co-location configuration compared to baseline. No significant differences in sociometric status between baseline and the co-location configuration were observed for OOW, OPSO, SOP1, SOP2 or PERI.

11.4 Centrality

The centrality of each node was not statistically significantly affected by scenario demand ($F_{1,81}=0.1$, $p>0.05$) but was significantly affected by operator role ($F_{8,81}=165.17$, $p<0.01$, $\eta_p^2=0.94$) and the interaction between scenario demand and role ($F_{8,81}=2.76$, $p<0.05$, $\eta_p^2=0.21$). When examining the effect of role post hoc analysis revealed OOW had statistically significantly ($p<0.05$) higher centrality than all operators. OPSO had statistically significantly higher centrality than all operators (except OOW). SOC had statistically significantly ($p<0.05$) higher centrality than all operators (except OPSO and OOW).

The centrality of each node was not statistically significantly affected by configuration type ($F_{1,162}=0.47, p>0.05$)

or the interaction of configuration type, role and demand ($F_{8,162} = 1.29, p > 0.05$). The interaction of configuration type and role statistically significantly affected sociometric status ($F_{8,162} = 55.84, p < 0.01, \eta_p^2 = 0.73$). Post hoc analysis revealed SOC, PERI and SHC had statistically significantly ($p < 0.05$) lower centrality in the co-location configuration than in the baseline condition. TMA1, TMA2, SOP1 and SOP2 had statistically significantly ($p < 0.05$) higher centrality in the co-location configuration compared to baseline.

11.5 Information network analysis

In the co-location configuration the structure of the information networks is relatively consistent in both high and low-demand RTPD scenarios with ‘contact’, ‘bearing’ and ‘course’ the most connected information pieces (see Fig. 3). The volume of emissions from most information elements appeared to increase in the high-demand RTPD scenarios although differences in relationships can be observed (see Tables 5, 6).

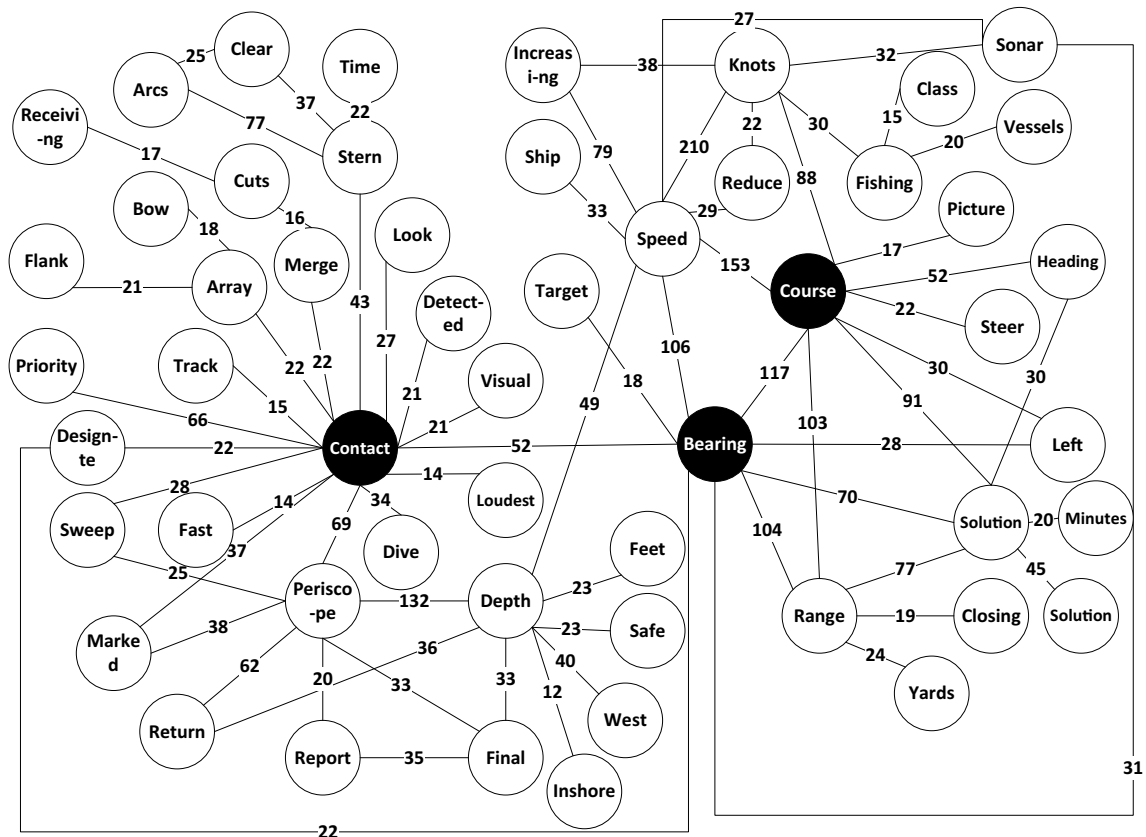


Fig. 3 Information network RTPD low-demand co-location configuration. The nodes with the highest centrality were similar to baseline, including contact, bearing and course (highlighted in black)

Table 5 Information network metrics for entire network RTPD co-location and baseline

	Baseline		Co-location		Demand co-location	Effect of configuration	Demand × configuration
	Low	High	Low	High			
Nodes	45.60 ± 5.10	44.40 ± 6.46	49.5 ± 5.95	55.1 ± 3.81	2.74*	17.31***	4.12
Edges	702.10 ± 330.28	644.80 ± 357.54	655.6 ± 130.36	776.8 ± 143.89	3.27*	0.16	3.04
Density	0.49 ± 0.15	0.49 ± 0.19	0.26 ± 0.04	0.26 ± 0.04	1.06	19.77***	0.16
Diameter	3.30 ± 0.82	3.5 ± 0.53	3.7 ± 0.67	3.8 ± 0.63	0.43	1.83	0.11
Total interaction	2412.10 ± 1424.21	2898.90 ± 2620.68	1864.00 ± 614.28	2597.40 ± 730.31	3.24***	0.46	0.16

* $p < 0.05$ *** $p < 0.001$

11.6 Whole network metrics

In the co-location configuration statistically significantly more emissions ($t_9 = 3.24$, $p < 0.05$, $d = 1.20$), nodes ($t_9 = 2.74$, $p < 0.05$, $d = 1.20$) and edges ($t_9 = 3.27$, $p < 0.05$, $d = 1.20$) in the high-demand condition compared to low demand (see Table 5), indicating that the overall structure of information varied based upon scenario demand. Configuration statistically significantly affected the number of nodes ($F_{1,18} = 17.31$, $p < 0.01$, $\eta_p^2 = 0.49$) and network density ($F_{1,18} = 19.78$, $p < 0.01$, $\eta_p^2 = 0.52$). The overall network density was statistically significantly ($p < 0.05$) lower in the co-location configuration compared to baseline, but the number of nodes were statistically significantly ($p < 0.05$) higher in the co-location configuration compared to baseline.

12 Nodal metrics

12.1 Emissions

In the co-location configuration the total emissions of each node were statistically significantly affected by scenario demand ($F_{1,126} = 40.36$, $p < 0.01$, $\eta_p^2 = 0.24$) and concept type ($F_{13,126} = 15.98$, $p < 0.01$, $\eta_p^2 = 0.62$). A statistically significant ($F_{13,126} = 2.54$, $p < 0.01$, $\eta_p^2 = 0.21$) interaction between demand and concept was also observed. Emissions were statistically significantly higher ($p < 0.05$) in the high-demand RTPD condition than the low-demand condition. Further analysis revealed bearing, contact, course, speed and solution had statistically significantly ($p < 0.05$) more emissions than all other information (see Fig. 3; Table 6). The total emissions of each node were statistically significantly affected by configuration type $F_{1,252} = 15.59$, $p < 0.05$, $\eta_p^2 = 0.15$. The total number of

emissions was statistically significantly ($p < 0.05$) lower in the co-location configuration.

12.2 Receptions

In the co-location configuration the total receptions of each node were statistically significantly affected by scenario demand ($F_{1,126} = 40.36$, $p < 0.01$, $\eta_p^2 = 0.24$) and concept type ($F_{13,126} = 15.98$, $p < 0.01$, $\eta_p^2 = 0.62$). A statistically significant ($F_{13,126} = 2.54$, $p < 0.01$, $\eta_p^2 = 0.21$) interaction between demand and concept was also observed. Receptions were statistically significantly higher ($p < 0.05$) in the high demand RTPD condition than the low demand condition. Further analysis revealed bearing, contact, course, speed and solution had statistically significantly ($p < 0.05$) more receptions than all other information. The total receptions of each node were statistically significantly affected by configuration type $F_{1,252} = 15.59$, $p < 0.05$, $\eta_p^2 = 0.15$. The total number of receptions was statistically significantly ($p < 0.05$) lower in the co-location configuration.

12.3 Sociometric status

In the co-location configuration the sociometric status of each node was statistically significantly affected by scenario demand ($F_{1,126} = 16.41$, $p < 0.01$, $\eta_p^2 = 0.28$) and concept type ($F_{13,126} = 17.50$, $p < 0.01$, $\eta_p^2 = 0.64$). A statistically significant ($F_{13,126} = 1.92$, $p < 0.05$, $\eta_p^2 = 0.17$) interaction between demand and concept was also observed. Sociometric status was statistically significantly ($p < 0.05$) higher in the high demand condition. Further analysis revealed bearing, contact, course, speed, periscope, depth range and solution had statistically significantly ($p < 0.05$) higher sociometric status than all other information. The sociometric status of each node was

Table 6 Information network metrics for individual nodes RTPD low- and high-demand scenario baseline and co-location

	Emission				Reception			
	Baseline		Co-location		Baseline		Co-location	
	Low	High	Low	High	Low	High	Low	High
Bearing	206.30 ± 158.06	270.10 ± 234.33	96.3 ± 34.82	170.7 ± 75.07	206.30 ± 158.06	255.30 ± 193.91	96.3 ± 34.82	170.7 ± 75.07
Contact	94.90 ± 37.02	146.10 ± 84.67	109.4 ± 40.69	168.7 ± 66.6	94.90 ± 37.02	152.60 ± 102.86	109.4 ± 40.69	168.7 ± 66.6
Course	178.36 ± 104.45	201.25 ± 165.25	113.7 ± 40.02	144.2 ± 43.34	178.36 ± 104.45	207.73 ± 179.15	113.7 ± 40.02	144.2 ± 43.34
Look	79.58 ± 36.75	67.22 ± 34.71	41.6683 ± 15.54	60.4 ± 18.6	79.58 ± 36.75	66.17 ± 36.49	41.683 ± 15.54	60.4 ± 18.6
Merge	89.76 ± 67.57	71.40 ± 73.51	21.2697 ± 10.06	34.7 ± 20.86	89.76 ± 67.57	77.90 ± 92.31	21.27 ± 10.06	34.7 ± 20.86
Periscope	115.59 ± 105.10	122.94 ± 158.76	94.1 ± 41.96	87.9 ± 37.04	115.59 ± 105.10	112.16 ± 125.55	94.1 ± 41.96	87.9 ± 37.04
Priority	38.60 ± 22.83	74.80 ± 60.15	29.9 ± 34.41	53 ± 32.37	38.60 ± 22.83	73.60 ± 56.87	29.9 ± 34.41	53 ± 32.37
Solution	183.60 ± 178.31	164.30 ± 144.30	88.7 ± 35.03	161.9 ± 70.11	183.60 ± 178.31	164.50 ± 144.83	88.7 ± 35.03	161.9 ± 70.11
Sonar	68.90 ± 96.73	130.79 ± 237.70	41.205 ± 41.1	70 ± 93.23	68.90 ± 96.73	161.70 ± 331.01	41.205 ± 41.1	70 ± 93.23
Speed	188.40 ± 103.97	251.15 ± 207.59	123.7 ± 47.89	163.3 ± 59.85	188.40 ± 103.97	249.66 ± 201.04	123.7 ± 47.89	163.3 ± 59.85
Sweep	32.90 ± 15.82	31.70 ± 21.28	17.1 ± 7.23	20.6 ± 7.79	32.90 ± 15.82	28.77 ± 15.11	17.1 ± 7.23	20.6 ± 7.79
Depth	133.03 ± 108.82	112.52 ± 81.57	87.4 ± 71.79	86.6907 ± 29.89	133.03 ± 108.82	109.37 ± 73.45	87.4 ± 71.79	86.697 ± 29.89
Range	133.80 ± 156.47	170.01 ± 121.53	75.2 ± 32.77	108.9353 ± 49.4	133.80 ± 156.47	173.27 ± 128.13	75.2 ± 32.77	108.953 ± 49.4
Visual	34.94 ± 19.80	22.42 ± 29.50	23.8567 ± 17.35	24.7361 ± 29.08	34.94 ± 19.80	24.45 ± 34.35	23.867 ± 17.35	24.731 ± 29.08
Demand co-location	5.35*		40.36***		4.91*		40.36***	
Concept co-location	3.52***		15.98***		3.22***		15.98***	
Demand × concept co-location	1.22		2.54***		1.20		2.54***	
Configuration	15.91***				15.39***			
Configuration × concept	0.73				0.67			
Configuration × role × demand	0.79				0.85			
Sociometric								
	Centrality				Centrality			
	Baseline		Co-location		Baseline		Co-location	
	Low	High	Low	High	Low	High	Low	High
Bearing	9.72 ± 7.62	11.63 ± 8.36	3.8905 ± 1.26	6.2308 ± 2.6	30.33 ± 3.55	30.08 ± 4.85	30.0573 ± 4.21	33.6362 ± 2.61
Contact	4.59 ± 1.58	6.62 ± 3.39	4.484 ± 1.63	6.1568 ± 2.36	29.9 ± 5.02	31.65 ± 4.77	35.5543 ± 4.74	40.9088 ± 3.27
Course	8.18 ± 4.73	8.48 ± 6.32	4.6726 ± 1.75	5.2595 ± 1.39	28.54 ± 4.67	28.42 ± 3.30	31.5647 ± 3.57	33.5329 ± 3.26
Look	3.53 ± 1.74	3.14 ± 1.7	1.7311 ± 0.68	2.2065 ± 0.66	26.9 ± 3.2	25.94 ± 3.83	29.0948 ± 4.72	33.805 ± 3.59
Merge	3.87 ± 2.97	3.39 ± 3.24	0.8922 ± 0.47	1.2697 ± 0.75	25.26 ± 5.41	23.82 ± 4.45	25.2503 ± 2.87	29.0633 ± 3.1
Periscope	5.25 ± 5.05	5.07 ± 5.21	3.8882 ± 1.85	3.2022 ± 1.31	27.8 ± 4.23	24.97 ± 5.23	33.1148 ± 3.55	33.986 ± 2.3
Priority	1.72 ± 0.87	3.39 ± 2.4	1.2161 ± 1.37	1.9245 ± 1.17	24.36 ± 4.63	25.80 ± 3.95	25.9366 ± 4.77	32.7191 ± 4.35
Solution	8.16 ± 8.66	6.97 ± 5.31	3.5851 ± 1.29	5.861 ± 2.33	28.57 ± 4.74	28.07 ± 5.97	31.4667 ± 4.82	35.8282 ± 3.37
Sonar	3.22 ± 4.74	6.07 ± 10.81	1.6158 ± 1.56	2.594 ± 3.52	24.86 ± 4.16	26.46 ± 5.30	27.689 ± 5.44	30.4183 ± 5.09
Speed	8.48 ± 4.82	11.11 ± 7.85	5.0648 ± 1.97	6.006 ± 2.28	28.45 ± 5.31	28.09 ± 5.45	30.3725 ± 4.36	33.4244 ± 2.46
Sweep	1.48 ± 0.72	1.33 ± 0.69	0.7049 ± 0.31	0.7603 ± 0.31	23.24 ± 3.77	22.04 ± 3.56	24.6863 ± 2.95	27.4126 ± 1.53

Table 6 (continued)

	Sociometric			Centrality		
	Baseline		Co-location	Baseline		Co-location
	Low	High		Low	High	
Depth	5.96 ± 4.93	4.88 ± 2.96	3.6763 ± 3.17	28.11 ± 4.37	26.10 ± 4.47	30.8825 ± 3.45
Range	6.34 ± 7.68	7.54 ± 5.06	3.063 ± 1.23	26.21 ± 3.44	25.87 ± 3.99	28.124 ± 4.04
Visual	1.53 ± 0.85	0.94 ± 1.2	0.9789 ± 0.71	22.8 ± 3.79	20.73 ± 3.27	25.736 ± 3.02
Demand co-location	3.31 [†]		16.41***	1.30		59.79***
Concept co-location	3.85***		17.50***	5.36***		14.07***
Demand × concept co-location	1.25		1.92*	0.67		1.02
Configuration	29.96***			1.33.37***		
Configuration × concept	1.00			1.30		
Configuration × role × demand	0.85			0.30		

* $p < 0.05$ *** $p < 0.001$

statistically significantly affected by configuration type ($F_{1,252} = 29.96, p < 0.01, \eta_p^2 = 0.11$). Sociometric status was statistically significantly ($p < 0.05$) lower in the co-location configuration.

12.4 Centrality

In the co-location configuration the centrality of each node was statistically significantly affected by scenario demand ($F_{1,126} = 59.79, p < 0.01, \eta_p^2 = 0.60$) and concept type ($F_{13,126} = 5.36, p < 0.01, \eta_p^2 = 0.36$). Centrality was statistically significantly ($p < 0.05$) higher in the high demand condition. Further analysis revealed that contact had statistically significantly ($p < 0.05$) higher centrality than all other information. The centrality of each node was statistically significantly affected by configuration type ($F_{1,252} = 133.37, p < 0.01, \eta_p^2 = 0.35$). Centrality was statistically significantly ($p < 0.05$) lower in the co-location configuration.

12.5 Task network analysis

The type of tasks completed by the command team was the same during baseline and the co-location configuration (for both high and low-demand scenarios) as the fundamental task completed by operators did not change (see Fig. 4). The task with the highest number of emissions was ‘building the sonar picture’ which required the completion of numerous subtasks (i.e. data analysis and assimilation) to inform the generation of a tactical picture when operating at depth (see Table 7).

12.6 Task frequency analysis

In the co-location configuration the frequency of task completion was statistically significantly affected by scenario demand ($F_{1,189} = 131.26, p < 0.01, \eta_p^2 = 0.41$) and task type ($F_{20,189} = 32.01, p < 0.01, \eta_p^2 = 0.77$). A statistically significant interaction ($F_{20,189} = 20.35, p < 0.01, \eta_p^2 = 0.68$) between scenario demand and task type was also observed. Post hoc analysis revealed the frequency of tasks completion was statistically significantly higher ($p < 0.05$) in the high-demand condition than the low-demand condition. The tasks detecting, designating, classifying, generating speed estimates and solutions from sonar were completed statistically significantly ($p < 0.05$) more frequently in the high demand condition. Further analysis revealed the tasks of detecting, classifying, generating speed estimates, and generating solution estimates from sonar were completed statistically significantly ($p < 0.05$) higher than all other tasks (see Table 7). All periscope related tasks (except detect and designate visual

contacts) were completed statistically significantly ($p < 0.05$) less than all other tasks (except clear stern arcs and final reports).

The frequency of task completion was statistically significantly affected by configuration ($F_{1,378} = 13.11, p < 0.01, \eta_p^2 = 0.43$), the interaction of configuration and task type ($F_{20,378} = 2.02, p < 0.01, \eta_p^2 = 0.10$) and the interaction of configuration, task type and demand ($F_{20,378} = 2.54, p < 0.01, \eta_p^2 = 0.12$). Further analysis revealed statistically significantly ($p < 0.05$) more tasks were completed in the co-location configuration than the baseline configuration. The tasks of detecting visual and designating visual were completed statistically significantly ($p < 0.05$) more frequently in the co-location configuration than in baseline (in both the low and high demand conditions). The tasks of detecting and designating sonar contacts were completed statistically significantly ($p < 0.05$) more frequently in the high-demand co-location configuration than in the high-demand baseline configuration.

13 Discussion for the co-location configuration

In the co-location configuration, the effect of demand was similar to what was observed during baseline, with significantly more communications between operators being observed (Stanton et al. 2017). However, communications were distributed more evenly across the command team with a greater number of edges observed (i.e. more operators directly communicating) and greater cohesion. The facilitation of communication between more operators has the potential to facilitate knowledge generation at the level of the team (Fiore et al. 2010; Klein et al. 2006; Cooke et al. 2008). However, it is important that any increase in verbal communications is necessary and are not occurring simply due to the fact that the co-location configuration has facilitated them, or in fact required them due to information transition being made more difficult (Salas et al. 2001; Stanton 2011; Carletta et al. 2000). This does not seem to be the case as the difference between the high- and low-demand scenarios in the co-location configuration was much greater than in baseline (Stanton et al. 2017). It appears that the co-location configuration has enabled greater volumes of communication, which was utilised in the high demand scenarios. At the same time however, it also appears to have facilitated greater efficiency, with much lower verbal communications observed in the low-demand scenarios. The additional capacity was only utilised when required operationally. The bottleneck that was observed in baseline between OPSO and SOC was reduced, with communication between these

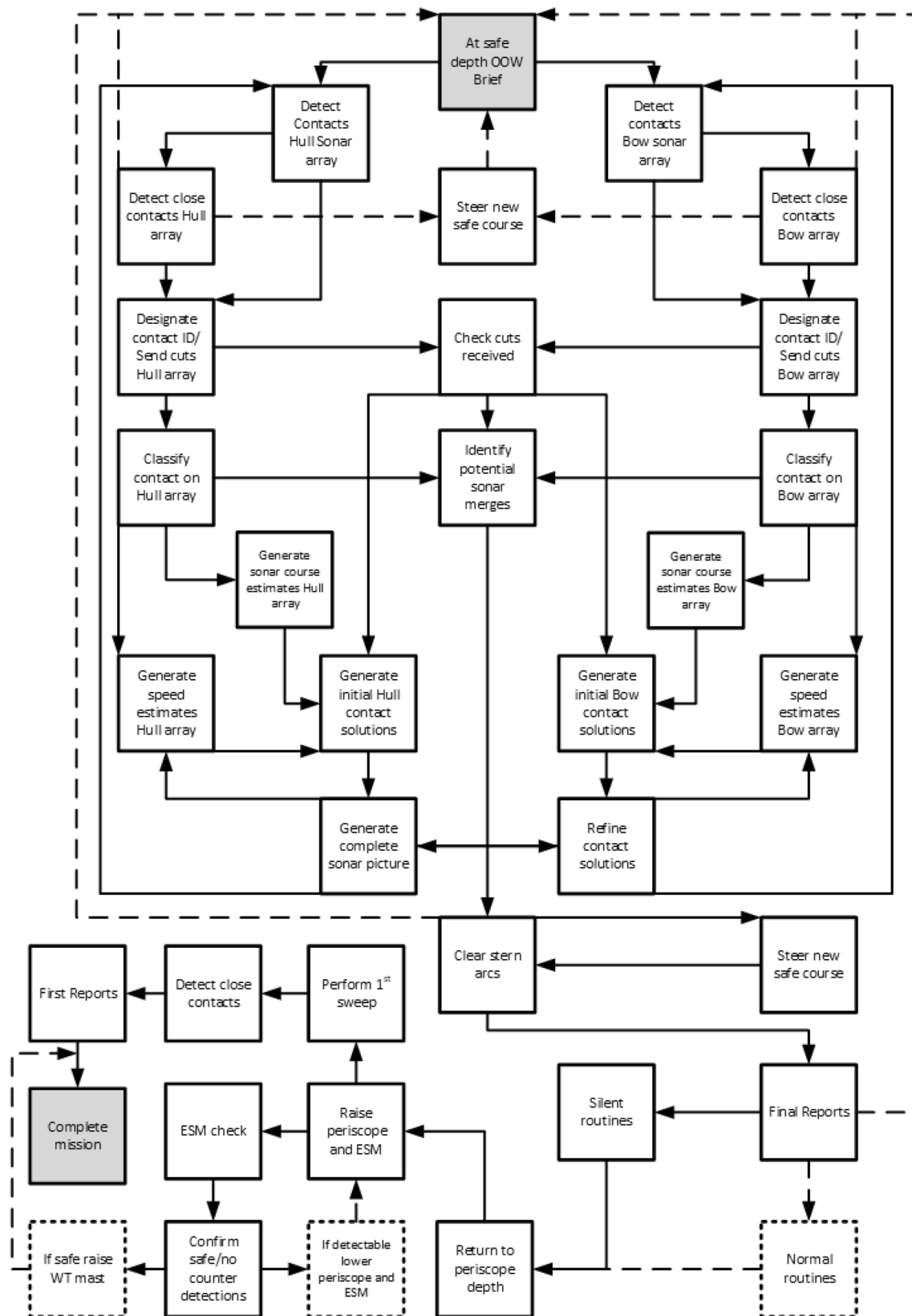


Fig. 4 Task network diagram for RTPD low- and high-demand scenarios

Table 7 Task network metrics for individual nodes RTPD scenarios high- and low-demand scenarios (baseline and co-location configuration)

	Node metrics				Frequency of task completion			
	Emis- sion	Reception	Sociomet- ric	Cent- rality	Baseline low	Baseline high	Co-location low	Co-location high
Detect contacts sonar	3	2	0.19	12.59	4 ± 1.89	8.7 ± 4.22	3.1 ± 1.66	12.4 ± 2.91
Designate sonar contact	2	2	0.15	11.35	3.3 ± 1.64	7.7 ± 4.85	2.5 ± 1.27	10.7 ± 3.89
Classify Sonar Contacts	3	1	0.15	11.72	3.8 ± 1.87	10.5 ± 4.3	2.6 ± 1.78	9.4 ± 3.6
Speed estimates	1	3	0.15	11.07	5.4 ± 2.27	10.9 ± 5.67	4.2 ± 2.2	10.9 ± 3.84
Sonar courses	1	1	0.08	10.29	1.2 ± 1.23	4.9 ± 2.13	4.9 ± 1.45	5.1 ± 3.21
Check cuts are received	2	1	0.12	11.35	2.4 ± 1.84	3.9 ± 1.52	3.5 ± 2.07	6.6 ± 4.17
Identify SONAR merges	2	2	0.15	12.24	3.4 ± 1.35	2.8 ± 1.81	3.3 ± 1.34	6.8 ± 2.74
Generate Solutions	1	3	0.15	12.66	4.6 ± 1.96	10.7 ± 3.53	4 ± 0	12.2 ± 2.86
Refine solutions	3	3	0.23	14.14	4.2 ± 3.58	5.1 ± 3.63	4.7 ± 3.27	5 ± 3.2
Submarine parameters	2	2	0.15	13.04	4.4 ± 2.46	4.3 ± 2.06	4.8 ± 1.32	4 ± 1.33
Raise Periscope	2	2	0.15	18.11	1 ± 0	0.8 ± 0.42	1 ± 0	1 ± 0
Complete Sweep	1	1	0.08	16.85	1.8 ± 0.63	0.8 ± 0.42	1.7 ± 0.48	1.1 ± 0.32
Detect Visual contacts	1	1	0.08	14.61	1.7 ± 0.95	1.4 ± 1.07	3.7 ± 0.67	3.9 ± 1.85
Total tasks completed					48.20 ± 9.07	80.50 ± 15.87	55.30 ± 8.41	96.90 ± 14.38
		Baseline		Co-location				
Effect of demand (co-location)		57.41***		131.26***				
Effect of task type (co-location)		25.20***		32.01***				
Demand × task (co-location)		7.09***		20.35***				
Effect of configuration		13.10***						
Effect of configuration × task		2.02*						
Effect of configuration × task × demand		2.54***						

* $p < 0.05$ *** $p < 0.001$

operators seeing the greatest reductions (Stanton et al. 2017). Simultaneously, communication between the SOPs and TMAs have greatly increased. It appears that co-locating the SOPs and TMAs operators, who are dependent on each other for task-relevant information, has created a more cohesive social network and placed less demand on OPSO and SOC to act as information brokers between the sound room and picture room (Loft et al. 2015a, b).

When examining information composition, the effect of demand in the co-location configuration was also similar to that observed during baseline, with more interactions between information nodes observed in high demand (Stanton et al. 2017). However, in the high demand co-location configuration there were significantly more nodes and edges (despite less overall interactions), indicating greater connectivity between information. The opposite of this was observed during baseline, suggesting the new configuration has facilitated greater flexibility in terms of how information was structured when being passed between operators (Stanton et al. 2017). It also appears the co-location of task

dependant operators has facilitated timely information transition as it is requested, rather than when an operator had the opportunity to pass information, removing production blocking mechanisms (Stanton et al. 2003). This is further verified by the fact that the density of the networks were significantly lower in the co-location. Information is no longer being repeatedly passed via multiple operators, in different orders and containing information that has not been requested. This highlights how the configuration of a team and supporting technology can greatly improve the effectiveness of overall team functionality (Stanton et al. 2015a, b; Espevik et al. 2006).

In the co-location configuration, the centrality of the TMA operators was significantly higher than in baseline, providing further verification of their increased importance to the social and information network composition (Stanton et al. 2017). However, the operator with the greatest centrality remained the OOW; this operator is required to interpret the range of information from different operators to make tactical decisions (Duryea et al. 2008). It should also be

noted that the volume of communications between the junior operators (SOPS and TMAs) and their direct superiors (SOC and OPSO, respectively) remained comparable to baseline. This interaction is important for quality checking and supervision purposes, critical processes in team cognition and reducing the potential for loafing to occur (Fiore et al. 2010; Klein et al. 2006; Cooke et al. 2008; Simms and Nichols 2014; Suleiman and Watson 2008). This reveals that whilst changes to the structure of the task and information networks have occurred, some fundamental components have remained the same. A further example of this is the fact that there was no significant difference in the prevalence of information when compared to baseline (Stanton et al. 2017). The nodes with the highest sociometric status in the high- and low-demand co-location configurations were similar to those observed in baseline. This suggests that whilst the structure of information transition has changed the content has not, important information is being retained, but transition and structure is more efficient.

Once again when examining the effect of demand on task completion in the co-location configuration, findings were comparable to baseline, with more tasks being completed in high demand due to the greater number of contacts to manage (Stanton et al. 2017). When examining the type of tasks most frequently completed during the high demand scenario in the co-location configuration, it is clear that tasks relating to the development of a tactical picture (i.e. detecting contacts and generating solutions), were completed more frequently as this ensures a safe RTPD (Stanton 2014; citation). However, when directly comparing the co-location configuration to baseline a significantly greater number of

tasks were completed overall in both high and low-demand scenarios. The co-location of operators dependant on each other for task-relevant information had increased overall productivity (Simms and Nichols 2014; Suleiman and Watson 2008; Stanton et al. 2003). When examining individual subtask completion, fundamental tasks (e.g. detecting, designation and generating solutions of contacts) remained similar during the low demand (when compared to baseline) but increased during the high demand, suggesting the new configuration has facilitated greater flexibility in productivity, with greater range in sub-task completion. This offers support for the fact that during baseline, productivity was blocked by the design of the system, which became apparent when capacity was being exceeded in the high demand scenarios (Stanton et al. 2003). The new configuration has facilitated greater flexibility in communication, structure of information transition and productivity (task completion) highlighting how the design of sociotechnical systems can be optimised to maximise human–technology–human interactions (Roco and Bainbridge 2003; Showalter 2005; Walker et al. 2009).

14 Results for the reduced crew size

14.1 Social network analysis

In the reduced crew size condition the average frequency of communications between operators in the command team varied depending on command team role and scenario demand (see Fig. 5). The overall composition of

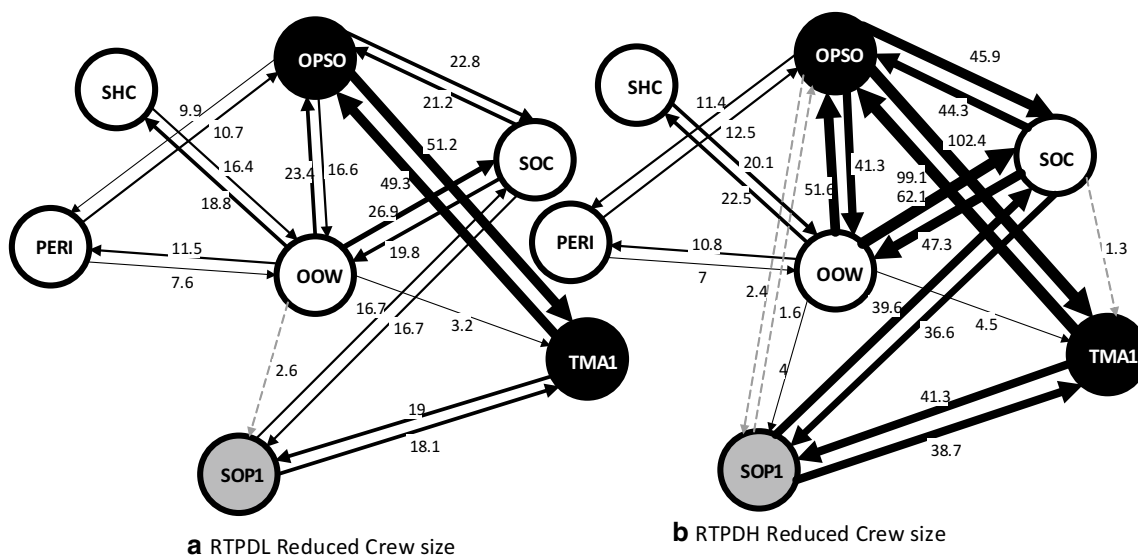


Fig. 5 Social network diagrams reduced crew size. OPSO and OOW had the largest volume of emissions and receptions of all operators, although the greatest number of communications was observed

between OPSO and TMA1 (highlighted in black). The communication between SOP1 and TMA1 greatly increased when compared to baseline (highlighted in grey)

Table 8 Social network metrics for whole network low- and high-demand RTPD baseline and reduced crew size condition

	RTPD				Effect of demand reduced crew size	Effect of crew size
	Baseline configuration		Reduced crew size condition			
	Low	High	Low	High		
Nodes	9	9	7	7	NA	NA
Edges	36.80 ± 3.01	36.50 ± 4.93	21.4 ± 2.22	22.10 ± 1.52	0.81	230.59***
Density	0.51 ± 0.04	0.51 ± 0.07	0.51 ± 0.05	0.53 ± 0.04	0.80	0.51
Cohesion	0.34 ± 0.03	0.35 ± 0.03	0.47 ± 0.06	0.48 ± 0.04	0.37	80.19***
Total interactions	663.80 ± 206.32	816.10 ± 221.10	418.90 ± 69.33	749.50 ± 124.79	8.90***	6.12*

* $p < 0.05$ *** $p < 0.001$

both networks is similar, however the volume of interactions between operators increased during the high demand reduced crew size RTPD scenarios.

14.2 Whole network metrics

The total interactions ($t_9 = -8.90$, $p < 0.05$, $r = 0.95$) statistically significantly increased in the high-demand reduced crewsize condition configuration. The total number of edges ($F_{1,18} = 230.59$, $p < 0.05$, $\eta_p^2 = 0.93$), total interactions ($F_{1,18} = 6.12$, $p < 0.05$, $\eta_p^2 = 0.25$), and cohesion ($F_{1,18} = 80.19$, $p < 0.01$, $\eta_p^2 = 0.82$) of the entire networks were statistically significantly affected by configuration type. This indicates that the structure of the networks fundamentally changed as a result of the reduced crew size, but such differences were effected by demand (see Table 8; Fig. 5).

15 Nodal metrics

15.1 Emissions

In the reduced crew size condition the total emissions of each node were statistically significantly affected by scenario demand ($F_{1,63} = 248.77$, $p < 0.01$, $\eta_p^2 = 0.80$) and operator role ($F_{6,63} = 86.01$, $p < 0.01$, $\eta_p^2 = 0.89$). The interaction of scenario demand and role also statistically significantly affected total node emissions ($F_{6,63} = 19.19$, $p < 0.01$, $\eta_p^2 = 0.65$). When examining the effect of scenario demand post hoc analysis revealed overall, emissions were statistically significantly higher ($p < 0.05$) in the high demand RTPD condition than the low-demand condition. All operators except PERI and SHC had statistically significantly more emissions in the high demand condition than the low-demand condition. When examining the effect of role post hoc analysis revealed that OPSO

had statistically significantly higher ($p < 0.05$) emissions than all other operators (see Table 9; Fig. 5). OOW had statistically significantly ($p < 0.05$) more emissions than all operators except OPSO and TMA1. TMA1 had statistically significantly ($p < 0.05$) more emissions than all operators except OPSO, OOW and SOC. When examining the interaction between demand and role post hoc analysis revealed that OPSO had statistically significantly ($p < 0.05$) more emissions than OOW in the high demand condition but not in the low-demand condition.

The total emissions of each node were not statistically significantly affected by reduced crew size ($F_{1,126} = 1.87$, $p > 0.05$). The interaction of reduced crew size and role statistically significantly affected total emissions ($F_{6,126} = 11.67$, $p < 0.01$, $\eta_p^2 = 0.36$). A non-significant trend was observed for the interaction of reduced crew size, role and demand on emissions ($F_{6,126} = 1.24$, $p = 0.06$). Post hoc analysis revealed TMA1 had statistically significantly ($p < 0.05$) more emissions in reduced crew size condition than baseline condition. SOC and OPSO had statistically significantly ($p < 0.05$) less emissions in reduced crew size condition compared to baseline.

15.2 Receptions

In the reduced crew size condition the total receptions of each node were significantly affected by scenario demand ($F_{1,63} = 236.65$, $p < 0.01$, $\eta_p^2 = 0.79$) and operator role ($F_{6,63} = 90.27$, $p < 0.01$, $\eta_p^2 = 0.90$). The interaction of scenario demand and role also statistically significantly affected total node receptions ($F_{6,63} = 19.87$, $p < 0.01$, $\eta_p^2 = 0.65$). When examining the effect of scenario demand post hoc analysis revealed overall, receptions were statistically significantly higher ($p < 0.05$) in the high demand

Table 9 Social network metrics for individual nodes RTPD low and high demand scenarios for baseline and reduced crew size condition

	Emission			Reception		
	Baseline		Reduced crew size		Reduced crew size	
	Low	High	Low	High	Low	High
OOW	111.2 ± 32.44	117 ± 45.6	94.2 ± 18.62	155.5 ± 31.01	83.2 ± 30.5	94.5 ± 40.46
OPSO	158.2 ± 55.27	204.2 ± 52.97	112.4 ± 23.01	203.4 ± 36.98	161.7 ± 43.21	204.7 ± 49.82
SOC	141 ± 46.39	193.2 ± 54.35	64.7 ± 13.86	129.5 ± 25.28	143.8 ± 42.81	191.8 ± 50.93
SOP1	59.2 ± 34.98	64.5 ± 35.02	36.4 ± 14.68	80.1 ± 21.43	55.2 ± 34.14	72.9 ± 43.04
TMA1	36.9 ± 16.66	61.8 ± 23.19	72.9 ± 22.16	141.4 ± 38.38	52.7 ± 20.5	70.8 ± 18.82
PERI	33.7 ± 9.19	25.8 ± 17.19	20.3 ± 4.5	20.7 ± 4.64	26.7 ± 7.32	20.9 ± 14.56
SHC	23.3 ± 13.59	19.4 ± 10.15	18 ± 4.52	18.9 ± 4.84	24.1 ± 9.89	21 ± 7.72
Demand reduced crew	19.94***		248.77***		21.49***	
Role reduced crew	40.41***		86.02***		42.87***	
Demand X role reduced crew	3.43***		19.19***		2.77***	
Configuration	1.87				1.01	
Configuration X role	11.67***				9.51***	
Configuration X role X demand	2.04 [†]				1.90 [†]	
Sociometric						
Centrality						
	Baseline		Reduced crew size		Reduced crew size	
	Low	High	Low	High	Low	High
OOW	24.3 ± 7.46	26.44 ± 10.72	27.07 ± 4.97	45.28 ± 7.86	5.61 ± 0.35	5.77 ± 0.35
OPSO	39.99 ± 11.14	51.11 ± 12.52	38.03 ± 7.18	68.75 ± 12.03	5.4 ± 0.3	5.31 ± 0.24
SOC	35.6 ± 10.99	48.13 ± 12.91	22.82 ± 4.48	46.3 ± 10.05	5.78 ± 0.5	5.68 ± 0.22
SOP1	14.3 ± 7.58	17.18 ± 9.65	12.9 ± 4.93	27.4 ± 7.02	4.12 ± 0.34	4.12 ± 0.14
TMA1	11.2 ± 4.46	16.58 ± 4.81	25.08 ± 7.28	48.05 ± 12.39	3.91 ± 0.25	3.88 ± 0.15
PERI	7.55 ± 1.71	5.84 ± 3.85	7.35 ± 1.59	7.42 ± 1.53	4.94 ± 0.47	5.07 ± 0.7
SHC	5.93 ± 2.87	5.05 ± 2.17	6.38 ± 1.45	6.63 ± 1.62	4.05 ± 0.31	3.79 ± 0.12
Demand reduced crew	22.86***		251.68***		0.01	
Role reduced crew	44.29***		91.69***		39.41***	
Demand X role reduced crew	3.35***		20.06***		0.88	
Configuration	28.08***				1512.17***	
Configuration X role	10.92***				45.71***	
Configuration X role X demand	3.70***				0.77	

* $p < 0.05$ *** $p < 0.001$

RTPD condition than the low-demand condition. All operators had statistically significantly ($p < 0.05$) more receptions in the high-demand condition compared to the low-demand condition except PERI and SHC. When examining the effect of role post hoc analysis revealed that OPSO had statistically significantly higher ($p < 0.05$) receptions than all other operators (see Table 9; Fig. 5). SOC, OOW and TMA1 had statistically significantly ($p < 0.05$) more receptions than all operators (except OPSO), although no significant difference was observed between these operators.

The total receptions of each node were not statistically significantly affected by reduced crew size ($F_{1,126} = 1.87$, $p > 0.05$). The interaction of reduced crew size and role statistically significantly affected total receptions ($F_{6,126} = 11.62$, $p < 0.05$, $\eta_p^2 = 0.36$). A non-significant trend was observed for the interaction of reduced crew size, role and demand ($F_{6,126} = 1.90$, $p = 0.08$). Post hoc analysis revealed OPSO and SOC had statistically significantly ($p < 0.05$) less receptions in the reduced crew size condition than baseline. TMA1 had statistically significantly ($p < 0.05$) more receptions in the reduced crew size condition compared to baseline.

15.3 Sociometric status

In the reduced crew size condition the sociometric status of each node was significantly affected by scenario demand ($F_{1,63} = 251.68$, $p < 0.01$, $\eta_p^2 = 0.80$) and operator role ($F_{6,63} = 91.69$, $p < 0.01$, $\eta_p^2 = 0.90$). The interaction of scenario demand and role also statistically significantly affected sociometric status ($F_{6,63} = 20.06$, $p < 0.01$, $\eta_p^2 = 0.66$). When examining the effect of scenario demand post hoc analysis revealed overall sociometric status was statistically significantly higher ($p < 0.05$) in the higher demand RTPD condition than the low-demand condition. All operators had statistically significantly ($p < 0.05$) higher sociometric status in the high-demand condition compared to the low demand except PERI and SHC. When examining the effect of operator role post hoc analysis revealed OPSO had statistically significantly ($p < 0.05$) higher sociometric status than all other operators. OOW, SOC and TMA1 had statistically significantly ($p < 0.05$) higher sociometric status than all operators (except OPSO) although no significant difference was observed between these operators.

The sociometric status of each node was statistically significantly affected by reduced crew size ($F_{1,126} = 28.08$, $p < 0.01$, $\eta_p^2 = 0.18$) and the interaction of reduced crew size, role and demand ($F_{6,126} = 3.73$, $p < 0.05$, $\eta_p^2 = 0.15$). The interaction of reduced crew size and role statistically significantly affected sociometric status ($F_{6,126} = 10.91$, $p < 0.01$, $\eta_p^2 = 0.34$). Post hoc analysis revealed that sociometric status

statistically significantly ($p < 0.05$) increased in reduced crew size condition compared to baseline. Post hoc analysis revealed OOW and TMA1 had statistically significantly ($p < 0.05$) higher sociometric status in reduced crew size condition than in the baseline condition. Further analysis revealed OOW and OPSO had statistically significantly ($p < 0.05$) higher sociometric status in reduced crew size condition high demand than baseline high demand, but not in the low demand conditions.

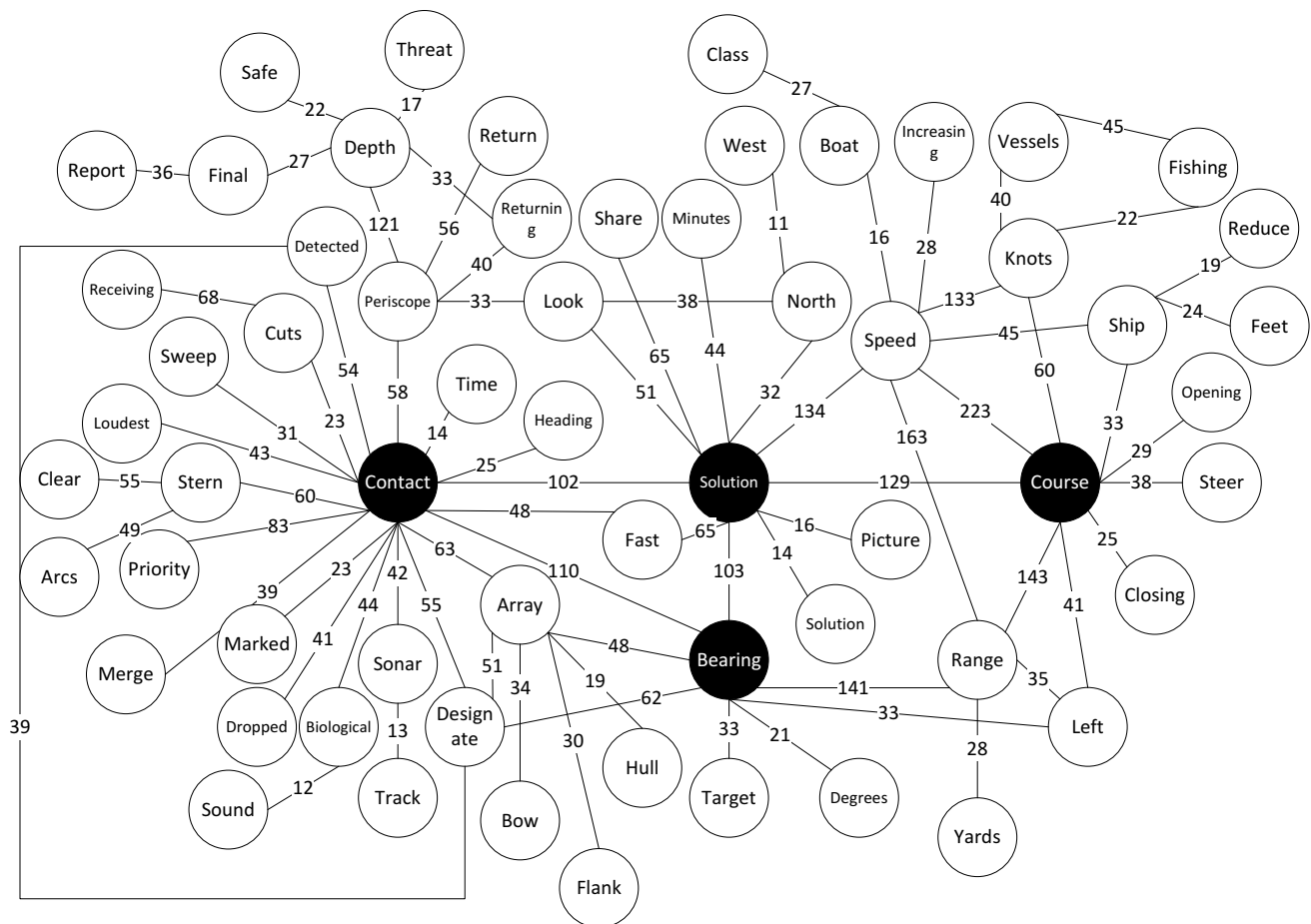
15.4 Centrality

In the reduced crew size condition the centrality of each node was not statistically significantly affected by scenario demand ($F_{1,63} = 0.8$, $p > 0.05$) or the interaction between scenario demand and role ($F_{6,63} = 0.67$, $p > 0.05$). Centrality was significantly affected by operator role ($F_{6,63} = 165.17$, $p < 0.01$, $\eta_p^2 = 0.94$). When examining the effect of role post hoc analysis revealed OOW had statistically significantly ($p < 0.05$) higher centrality than all operators. OPSO had statistically significantly higher centrality than all operators (except OOW). SOC had statistically significantly ($p < 0.05$) higher centrality than all operators (except OPSO and OOW). SOP1 and TMA1 had statistically significantly ($p < 0.05$) higher centrality than SHC and PERI, although no significant difference was observed between these operators.

The centrality of each node was statistically significantly affected by the reduced crew size ($F_{1,126} = 1512.17$, $p < 0.01$, $\eta_p^2 = 0.92$) but not by the interaction of crew size, role and demand ($F_{6,126} = 0.77$, $p > 0.05$). The interaction of crew size and role statistically significantly affected centrality ($F_{6,126} = 45.71$, $p < 0.01$, $\eta_p^2 = 0.69$). Post hoc analysis revealed that centrality statistically significantly ($p < 0.05$) decreased in reduced crew size condition compared to baseline. Post hoc analysis revealed all operators had statistically significantly ($p < 0.05$) lower centrality in reduced crew size condition than in the baseline condition.

15.5 Information network analysis

In the reduced crew size condition the structure of the information networks was relatively consistent in both high- and low-demand RTPD scenarios. However, the volume of information passed was greater in high demand, but differences in relationships can be observed depending on information type (see Fig. 6; Table 10).



15.6 Whole network metrics

The overall network density was statistically significantly ($p < 0.05$) lower in the reduced crew size configuration compared to baseline but the number of nodes was statistically significantly ($p < 0.05$) higher in the reduced crew size

16 Nodal metrics

In the reduced crew size configuration the total emissions of each node were statistically significantly affected by scenario

Table 10 Information network metrics for individual nodes RTPD low- and high-demand scenario baseline and reduced crew size

	Emission			Sociometric			Centrality		
	Baseline		Reduced crew size	Baseline		High	Baseline		Reduced crew size
	Low	High		Low	High		Low	High	
Bearing	206.30 ± 158.06	270.10 ± 234.33	72.5 ± 18.34	141.2 ± 34.33	9.72 ± 7.62	11.63 ± 8.36	30.33 ± 3.55	30.08 ± 4.85	29.1175 ± 2.46
Contact	94.90 ± 37.02	146.10 ± 84.67	95.3 ± 32.16	172.6 ± 68.21	4.59 ± 1.58	6.62 ± 3.39	29.9 ± 5.02	31.65 ± 4.77	34.5631 ± 4.25
Course	178.36 ± 104.45	201.25 ± 165.25	95.6 ± 31.26	147.4 ± 33.71	8.18 ± 4.73	8.48 ± 6.32	28.54 ± 4.67	28.42 ± 3.30	31.5912 ± 3.12
Look	79.58 ± 36.75	67.22 ± 34.71	26.1 ± 20.62	64.7 ± 44.13	3.53 ± 1.74	3.14 ± 1.7	26.9 ± 3.2	25.94 ± 3.83	26.1568 ± 2.53
Merge	89.76 ± 67.57	71.40 ± 73.51	13.267 ± 16.46	33.6109 ± 28.5	3.87 ± 2.97	3.39 ± 3.24	25.26 ± 5.41	23.82 ± 4.45	22.2189 ± 3.65
Periscope	115.59 ± 105.10	122.94 ± 158.76	85.3 ± 31.19	103.2972 ± 41.54	5.25 ± 5.05	5.07 ± 5.21	27.8 ± 4.23	24.97 ± 5.23	31.7898 ± 4.54
Priority	38.60 ± 22.83	74.80 ± 60.15	31 ± 11.37	52.6 ± 23.17	1.72 ± 0.87	3.39 ± 2.4	24.36 ± 4.63	25.80 ± 3.95	26.9289 ± 2.48
Solution	183.60 ± 178.31	164.30 ± 144.30	87.1 ± 60.77	142.8 ± 39.12	8.16 ± 8.66	6.97 ± 5.31	28.57 ± 4.74	28.07 ± 5.97	29.9179 ± 4.95
Sonar	68.90 ± 96.73	130.79 ± 237.70	33.2 ± 33.6	59.6 ± 76.44	3.22 ± 4.74	6.07 ± 10.81	24.86 ± 4.16	26.46 ± 5.30	27.1578 ± 4.39
Speed	188.40 ± 103.97	251.15 ± 207.59	90.5 ± 17.06	135.2 ± 47.95	8.48 ± 4.82	11.11 ± 7.85	28.45 ± 5.31	28.09 ± 5.45	30.5744 ± 3.28
Sweep	32.90 ± 15.82	31.70 ± 21.28	23.6 ± 16.69	25.3198 ± 17.28	1.48 ± 0.72	1.33 ± 0.69	23.24 ± 3.77	22.04 ± 3.56	25.0798 ± 2.59
Depth	133.03 ± 108.82	112.52 ± 81.57	79.5 ± 33.81	101.0685 ± 67.19	5.96 ± 4.93	4.88 ± 2.96	28.11 ± 4.37	26.10 ± 4.47	30.7947 ± 3.92
Range	133.80 ± 156.47	170.01 ± 121.53	47.9 ± 23.86	83.6635 ± 35.41	6.34 ± 7.68	7.54 ± 5.06	26.21 ± 3.44	25.87 ± 3.99	25.5399 ± 3.38
Visual	34.94 ± 19.80	22.42 ± 29.50	26.51 ± 22.04	40.4644 ± 39.08	1.53 ± 0.85	0.94 ± 1.2	22.8 ± 3.79	20.73 ± 3.27	24.9479 ± 2.53
Demand	5.35*	82.64***		3.31 [†]		50.56***	1.30		79.18***
Concept	3.52***	16.58***		3.85***		16.72***	5.36***		20.15
Demand × concept	1.22	2.25***		1.25		1.89*	0.67		1.12
Configuration	222.73**					37.25***			98.41***
Configuration × information	1.32			1.60			2.42***		
Configuration × information × demand	0.80			0.93			0.75		

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Table 11 Information network metrics RTPD baseline and reduced crew size

	Baseline		Reduced crew size		Effect of demand	Effect of configuration	Configuration × demand
	Low	High	Low	High			
Nodes	45.60 ± 5.10	44.40 ± 6.46	47.8 ± 5.37	54.7 ± 4.11	2.91*	15.55***	5.18*
Edges	702.10 ± 330.28	644.80 ± 357.54	552.8 ± 112.4	782 ± 168.92	3.12*	0.004	5.69*
Density	0.49 ± 0.15	0.49 ± 0.19	0.24 ± 0.03	0.26 ± 0.05	1.11	22.02***	0.1
Diameter	3.30 ± 0.82	3.5 ± 0.53	4.2 ± 0.92	3.2 ± 0.42	3.00*	1.47	9.53**
Total emissions	2412.10 ± 1424.21	2898.90 ± 2620.68	1556.99 ± 408.8	2305.16 ± 782.44	2.57*	0.89	7.53*

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

demand ($F_{1,126} = 82.64$, $p < 0.01$, $\eta_p^2 = 0.40$) and concept type ($F_{13,126} = 16.59$, $p < 0.01$, $\eta_p^2 = 0.63$). A statistically significant ($F_{13,126} = 2.52$, $p < 0.01$, $\eta_p^2 = 0.19$) interaction between demand and concept was also observed. Emissions were statistically significantly higher ($p < 0.05$) in the high-demand RTPD condition than the low-demand condition. Further analysis revealed bearing, contact, course, periscope, speed, depth and solution had statistically significantly ($p < 0.05$) more emissions than all other information. Emissions of bearing, contact, course and solution were statistically significantly ($p < 0.05$) higher in the high demand condition than the low demand condition. The total emissions of each node were statistically significantly affected by configuration type ($F_{1,252} = 22.73$, $p < 0.01$, $\eta_p^2 = 0.08$). The total number of emissions was statistically significantly ($p < 0.05$) lower in the reduced crew size configuration.

16.2 Receptions

In the reduced crew size configuration the total receptions of each node were statistically significantly affected by scenario demand ($F_{1,126} = 82.64$, $p < 0.01$, $\eta_p^2 = 0.40$) and concept type ($F_{13,126} = 16.59$, $p < 0.01$, $\eta_p^2 = 0.63$). A statistically significant ($F_{13,126} = 2.52$, $p < 0.01$, $\eta_p^2 = 0.19$) interaction between demand and concept was also observed. Receptions were statistically significantly higher ($p < 0.05$) in the high demand RTPD condition than the low-demand condition. Further analysis revealed bearing, contact, course, periscope, speed, depth and solution had statistically significantly ($p < 0.05$) more receptions than all other information. Receptions of bearing, contact, course and solution were statistically significantly ($p < 0.05$) higher in the high demand condition than the low-demand condition. The total receptions of each node were statistically significantly affected by configuration type ($F_{1,252} = 22.72$, $p < 0.01$, $\eta_p^2 = 0.08$). The total number of receptions was statistically significantly ($p < 0.05$) lower in the reduced crew size configuration.

16.3 Sociometric status

In the reduced crew size configuration the sociometric status of each node was statistically significantly affected by scenario demand ($F_{1,126} = 82.64$, $p < 0.01$, $\eta_p^2 = 0.40$) and concept type ($F_{13,126} = 16.72$, $p < 0.01$, $\eta_p^2 = 0.63$). A statistically significant ($F_{13,126} = 1.89$, $p < 0.05$, $\eta_p^2 = 0.16$) interaction between demand and concept was also observed. Sociometric status was statistically significantly higher ($p < 0.05$) in the high demand RTPD condition than the low-demand condition. Further analysis revealed bearing, contact, course, periscope, speed, depth and solution had statistically significantly ($p < 0.05$) more emissions than all other information. Bearing and contact had statistically significantly ($p < 0.05$) higher sociometric status in the high demand condition compared to the low-demand condition. The sociometric status of each node was statistically significantly affected by configuration type ($F_{1,252} = 37.25$, $p < 0.01$, $\eta_p^2 = 0.13$).

16.4 Centrality

In the reduced crew size configuration the centrality of each node was statistically significantly affected by scenario demand ($F_{1,126} = 79.18$, $p < 0.01$, $\eta_p^2 = 0.39$) and concept type ($F_{13,126} = 20.15$, $p < 0.01$, $\eta_p^2 = 0.68$). Centrality was statistically significantly ($p < 0.05$) higher in the high demand condition. Further analysis revealed that contact had statistically significantly ($p < 0.05$) higher centrality than all information. The centrality of each node was statistically significantly affected by configuration type ($F_{1,252} = 98.41$, $p < 0.01$, $\eta_p^2 = 0.28$). A statistically significant ($F_{13,252} = 2.42$, $p < 0.01$, $\eta_p^2 = 0.11$) interaction between configuration and information was also observed. Centrality was statistically significantly ($p < 0.05$) higher in the reduced crew size configuration compared to

Table 12 Frequency of task completion RTPD scenarios baseline and reduced crew size

Demand	RTPD			
	Baseline		Reduced crew size	
	Low	High	Low	High
Detect sonar contacts	4 ± 1.89	8.7 ± 4.22	2.6 ± 1.35	10.8 ± 3.71
Designate sonar contacts	3.3 ± 1.64	7.7 ± 4.85	2.6 ± 1.35	10 ± 3.56
Classify sonar contacts	3.8 ± 1.87	10.5 ± 4.3	1.8 ± 1.4	7.8 ± 4.42
Sonar speed estimates	5.4 ± 2.27	10.9 ± 5.67	2.9 ± 1.79	7.7 ± 2.98
Sonar course estimates	1.2 ± 1.23	4.9 ± 2.13	3.5 ± 1.84	4.6 ± 3.47
Check cuts	2.4 ± 1.84	3.9 ± 1.52	2.8 ± 1.75	6 ± 3.71
Sonar merges	3.4 ± 1.35	2.8 ± 1.81	2.8 ± 1.62	5.4 ± 3.24
Sonar solution	4.6 ± 1.96	10.7 ± 3.53	4.1 ± 0.32	10.9 ± 1.85
Refine solutions	4.2 ± 3.58	5.1 ± 3.63	3.9 ± 3.38	3.8 ± 3.68
Change submarine parameters	4.4 ± 2.46	4.3 ± 2.06	5.4 ± 1.35	5.6 ± 2.07
Raise periscope	1 ± 0	0.8 ± 0.42	1 ± 0	1 ± 0
Complete sweep	1.8 ± 0.63	0.8 ± 0.42	1.4 ± 0.52	1.3 ± 0.67
Detect visual contacts	1.7 ± 0.95	1.4 ± 1.07	3.7 ± 1.06	4.2 ± 2.04
Total tasks completed	48.20 ± 9.07	80.50 ± 15.87	49.10 ± 7.09	87.80 ± 19.89
Effect of demand	57.41***		125.33***	
Effect of task type	25.20***		20.38***	
Demand × task	7.09***		15.45***	
Configuration	1.71			
Configuration × task	2.77***			
Configuration × task × demand	1.65*			

* $p < 0.05$ *** $p < 0.001$

baseline. The centrality of contact was statistically significantly ($p < 0.05$) higher in the reduced crew size configuration compared to baseline.

16.5 Task network analysis

The type of tasks completed by the command team were the same during baseline and the reduced crew size configuration (for both high and low-demand scenarios) as the fundamental task completed by operators did not change. However, the frequency of task completion was effected (as with the co-location full team comparison to baseline).

In the reduced crew size condition the frequency of task completion was statistically significantly affected by scenario demand ($F_{1,189} = 125.33$, $p < 0.01$, $\eta_p^2 = 0.40$) and task type ($F_{20,189} = 20.39$, $p < 0.01$, $\eta_p^2 = 0.68$). A statistically significant interaction ($F_{20,189} = 15.45$, $p < 0.01$, $\eta_p^2 = 0.62$) between scenario demand and task type was also observed. Post hoc analysis revealed the frequency of tasks completion was statistically significantly higher ($p < 0.05$) in the high demand condition than the lowdemand condition. The tasks detecting, designating, classifying generating speed

estimates and generating solutions for sonar contacts were completed statistically significantly ($p < 0.05$) more in the high demand condition than the lowdemand condition. The tasks detecting, designating and generating sonar solutions were completed statistically significantly more than all periscope based tasks (e.g. visual detection, range and classify). The tasks classify sonar contacts, generate speed solutions and change own submarine parameters were completed more frequently than all other tasks except detect and designate visual contacts (and those already mentioned, see Table 12).

The frequency of task completion was not statistically significantly affected by crew size ($F_{1,378} = 1.47$, $p > 0.05$). It was statistically significantly affected by the interaction of crew size and task type ($F_{20,378} = 2.77$, $p < 0.01$, $\eta_p^2 = 0.13$) and the interaction of crew size, task type and demand ($F_{20,378} = 1.65$, $p < 0.05$, $\eta_p^2 = 0.08$). Further analysis revealed the tasks of detecting visual and designating visual were completed statistically significantly ($p < 0.05$) more frequently in reduced crew size condition than in baseline (in both the low and high demand conditions). The tasks of detecting and designating sonar contacts were completed statistically significantly ($p < 0.05$) more frequently in the

high demand reduced crew size configuration than all other conditions.

17 Discussion for the reduced crew size

The effect of scenario demand in the reduced crew size configuration was similar to what was observed for the full co-located team study and baseline. The command team communicated more frequently, with greater connectivity of information structure and a number of tasks being completed (Stanton et al. 2017). The similarities of information prevalence between baseline and the co-location configuration were also observed with a reduced crew size. Furthermore, as with the full crew in co-location the differences between the low and high demand scenarios were much greater, further highlighting that the new configuration appears to have increased capacity, but that capacity is only utilised when it is operationally relevant. This shows that, even with a reduced crew size, the command team had additional capacity when completing the low-demand scenarios. This can provide insights into when economic savings could be made (in terms of manning), but perhaps more importantly how data from new sensors and instruments might best be integrated into the command space, as the removed operators may have the capacity to process additional sensor information (Hamburger et al. 2011; Mankins 2009; Allender 2000).

When comparing the co-location configuration to baseline, the volume of communications between OPSO and TMA1 increased by the greatest amount, suggesting that OPSO was more involved in the TMA process rather than just delegating workload between operators (Stanton et al. 2017). This is verified by the fact that the sociometric status of OPSO increased far more than any operator when compared to baseline (particularly in high demand). A further contributing factor to this is the increased communication between OPSO and OOW, to assist with confirmation of the tactical picture (Roberts and Stanton 2018; Duryea et al. 2008). This highlights that whilst the co-location configuration has appeared to increase capacity it has placed additional cognitive load on OPSO (Roberts and Cole 2018; Baddeley 2000). This is in spite of the fact that the number of communications observed between SOP1 and TMA1 significantly increased, suggesting that the co-location of these operators facilitated coping with the additional demand resulting from reduced crew size. In the baseline configuration, there was a reliance on OPSO to act as an information broker between the sound and picture room (Stanton et al. 2017; Loft et al. 2015a, b).

It appears that a difference in command team strategy was observed in terms of information exchange with reduced crew size. In the low-demand conditions the sociometric

status of all operators was more even, suggesting that the tactical picture was developed organically in a bottom-up fashion (Roberts and Stanton 2018). However, in the higher demand scenarios the senior operators (OOW, OPSO and SOC) had much higher sociometric status, suggesting these operators were more involved in building the tactical picture in a top-down fashion. This may be due to the fact that the command team had reached workload capacity so was required to prioritise particular contacts (as the whole picture could not be processed) resulting in more communication load on senior operators (Duryea et al. 2008). This is further validated by the fact that a number of sub-tasks were completed more frequently in the reduced crew size configuration. The total number of sonar detections and designations increased (although not significantly), indicating the command teams needed to be aware of all contacts. However, the number of speed estimates, classifications and solutions decreased suggesting the command team were being required to prioritise which contacts to further process (Stanton 2014). Despite this, no significant differences in total task completion was observed between the reduced crew size and baseline, suggesting the co-location had increased capacity to cope with a reduced crew size. Although, smaller crew sizes have been associated with greater productivity as the potential to ‘loaf’ is reduced (Alnuaimi et al. 2010).

18 Summary and conclusions

The current work compared the functionality of submarine command teams completing a RTPD in a representation of a contemporary operational control room configuration (baseline), a co-location configuration and reduced crew size. The co-location configuration improved the efficiency of communications between operators, resulting in a change in structure of information transition and an increase of overall productivity with more tasks being completed compared to baseline (Stanton et al. 2017). The co-location configuration afforded greater flexibility in operational capacity with more pronounced differences between low and high demand scenarios also observed. Furthermore, the co-location configuration improved efficiency to facilitate coping with a reduced crew size, resulting in similar productivity to what was observed during baseline (Huddleston and Harris 2017; Schutte 2017). The co-location of operator's dependent on each other for task-relevant information reduced loafing which may have occurred due to production blocking resulting from engineering limitations observed in the baseline scenarios (Simms and Nichols 2014; Suleiman and Watson 2008; Stanton et al. 2003; Binns 2008; Burcher and Rydill 1995). These results offer insight into how sociotechnical systems can be optimised to obtain maximal utility from future technological advancements (Hamburger et al. 2011;

Mankins 2009; Roco and Bainbridge 2003; Showalter 2005; Walker et al. 2008). They also offer insights into where economic savings might be gained in such systems and where additional capacity might be found to cope with additional data processing requirements in the control room from technology upgrades and sensor advancements (Brynjolfsson and Hitt 2000; Devaraj and Kohli 2003; Hewish 2002).

The findings from this study show that co-location has benefits, but there are potential drawbacks to consider. First is the need to redesign control rooms that enable this reconfiguration to take place (Stanton et al. 2010). As Stanton et al. (2010) have shown, changing one aspect of the control room has knock-on effects to other aspects. Second, the size of the control room has to accommodate the more personnel, so merging the sound room and control room will mean finding a new location on board a submarine that can house the increased personnel. This is not a problem for most land-based control rooms. Finally, the reduced crew condition did stretch the team to their workload capacity in the higher demand scenario, to their point where they were prioritising contacts. This meant that there was no additional spare capacity to accommodate changes in priorities.

The current results offer insight into the development of submarine control rooms but also for wider control room design across many domains (Rudisill 2000; Bruce et al. 1998; Stanton et al. 2016; Santos et al. 2008). The removal of historic engineering based constraints offers avenues for improvements (Binns 2008; Burcher and Rydill 1995). However, a degree of caution is warranted as technological support (e.g. noise cancelling headphones) requires further investigation to examine the impact of such technology on actual task performance (Arrabito et al. 2005). Moreover, the economic savings associated with reducing crew size does not always consider the wider tasks undertaken by command team operators that would still require completion (e.g. cleaning, maintenance and extremely high workload situations). A primary consideration when reviewing reduced crewing should be an examination of overall sociotechnical system safety (Salotti et al. 2014; Huddleston and Harris 2017; Schutte 2017). Therefore, future work should examine how the changes to functionality detailed in the current studies impact on accuracy of tactical pictures, decision making and overall submarine safety and maintenance.

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