A human centred approach to optimise human performance in complex marine environments and habitable spaces.

Dr Peter Schumacher, University of South Australia, peter.schumacher@unisa.edu.au
Prof. Siobhan Banks, University of South Australia, siobhan.banks@unisa.edu.au

This project undertaken under DST Group Research Agreement: 6961

ABSTRACT

The design, size and layout of submarine habitable spaces impacts people's ability to work, rest, sleep, engage in exercise and recreation. In addition, attracting and retaining talented people is important for the future submarine force and living conditions and habitability are factors that impact retention. In addition, managing crew fatigue and subsequently increasing operational effectiveness, is a significant challenge to ensure optimum decision making under challenging circumstances; part of this is ensuring the environment is designed to meet user needs.

In order to develop better habitable spaces a human-centred design (HCD) development and assurance methodology, including the application of anthropometric data, was developed for the Australian Defence Science and Technology Group (DSTG). The first application of the method was the design of sleeping berths, galleys and messes for submarines. An HCD approach will develop environments that can help reduce mental and physiological fatigue enhancing submariner cognitive performance and decision making as well as improving recruitment and retention. While HCD is an established discipline it is underutilised in shipbuilding and the early implementation of HCD in projects will provide improved outcomes for users.

PURPOSE AND BENEFITS

The capacity for operators to assimilate and understand the data provided by complex systems is severely tested in 24/7, operational environments. In addition, high workload, stress, and extreme fatigue impair cognitive performance and increase errors during operationally critical tasks. The huge personal, financial and tactical cost of high workload, stress and fatigue while on deployment must be addressed if we are to perform better and faster. The new operational edge comes, not only from technology, but from optimised operators that can make superior decisions in an information dense and complex undersea environment. As part of this optimising the environment for rest and relaxation is an important fatigue countermeasure.

The need to recruit and retain personnel for future submarine crews presents challenges and shipboard quality of life is one of several non-work factors that impact retention (Schwerin, Kline, Olmsted & Wilcove, 2006). A survey of US Navy personnel found that unsatisfactory living conditions, such as lack of privacy and personal space, limited room in the cabin areas and berths as well as poor showers, head spaces and mattresses have a negative effect on performance and crew retention (Wilcove & Schwerin, 2008). The design of habitable spaces requires further research, including the development of mock ups and simulations, to better understand the relative importance of different features (Wilcove & Schwerin, 2008).

Finally, poor design decisions result in poor crew satisfaction and expensive refits. A review of the psychological and physiological impact of the submarine environment, specifically looking at the US Virginia Class SSN, found that poor design of the mess and berth had a negative impact on the quality of life. This was evidenced by a larger number of psychologically based waivers and disqualifications among SSN crews compared to SSBN and these were exacerbated on the Virginia class due to deficiency in the design of the habitation areas (Shobe et al., 2003).

INTRODUCTION

The myth that fatigue and stress can be overcome by adequate motivation has influenced military operations for decades (Shay 1998). However, this attitude is changing and the need to improve habitability on board submarines in order to improve crew performance is well established. In a military operating environment there are many stressors in addition to actual warfighting, ranging from reduced sleep, shift-work, social pressure, environmental conditions and operational environments that frequently involve long work hours and less than optimal sleep environments (Miller, Matsangas & Shattuck, 2008). A lack of sleep results in impaired cognitive performance (Banks & Dinges, 2007; Nebes et al., 2009). Habitability cannot be compromised to other elements without impacting crew performance (OPNAVINST, 1996) and '…improvements in cabin design could have significant effects on crew fatigue and overall effectives.' (Ponton & Parera, 2015) In this way habitability could be used as a fatigue countermeasure, protecting against deteriorations in cognitive performance and increased errors.

HCD is an element of ergonomic processes and it is described in standards such as ISO/TS 18152 Ergonomics of Human-System Interaction, however, despite the recommendations of the standards, HCD practices are not used in the early stages of ship building design and development (Genez et al., 2018). What is unique in this case is the implementation of HCD in the early stages of the project to develop an understanding of the user needs and an HCD focused assurance processes.

APPROACH

The HCD approach draws on expertise from industrial design, anthropometry and bio-behavioural psychology. The process has been developed to design habitable spaces using a range of human-centred design and co-design methods to investigate the user needs, wants, activities, habits, physical requirements and psycho/social needs. The application of anthropometry to ensure human fit includes physical models and digital-human-mannequins (DHMs) within CAD and VR and using the human simulation software, JACK™, to evaluate designs. The Royal Australian Navy Submarine Force was involved throughout the project as part of the development of the design exemplars.

HCD is a framework for product development that involves the end users perspective in all steps of the design process. HCD practice emphasises user engagement methods such as observation and interviews as well as participatory design, co-design and contextual design techniques for investigating and describing the interactions between people and their environments (Beyer, Holtzblatt, 1997).

What people do while on watch and at work while onboard is governed by predetermined procedures and processes that are used to inform the design of the work environment.

However, this does not account for everything people do while working or what people do when not on watch or at work and are using their own time for their own purposes. These day-to-day activities on submarines are not well understood by non-submariners.

Submarine habitable environments are unique due to the extreme space restrictions, challenging watch keeping schedules and complicated technical context. As a result the design team, who have probably never experienced these extreme living conditions, cannot draw on their own personal experiences to understand how these environments are used. Even the simplest day-to-day activities on submarines are very different to 'top-side' activities, for example, taking a shower or having a meal. The HCD methods investigate these activities so that the submariner's actions and needs are recorded and made explicit so that design team can develop better environments that meet the submariner's requirements. Without this understanding the design team risks making uninformed and poor decisions resulting in sub-optimal living environments that impact of the submariner's quality of life.

A second element of the project was the application of anthropometry to ensure the best physical fit of the environment for the range of body shapes and sizes in the user population. This utilised the Anthropometry Survey of the Royal Australian Navy (ASRAN) (Ponton et al., 2019) data gathered specifically to support Navy ship building in Australia. The design for human fit involved the application of standards, anthropometric data, the Maritime Physical Accommodation Guidance for the Royal Australian Navy (MPAGRAN) (Ponton, 2019) and the use of DHMs based on the ASRAN data.

The DHMs were made in SolidWorks™ so that the design team could include dimensionally accurate human figures from the ASRAN data in the CAD model at all stages of the design development process. The DHMs were also used in VR to understand what spaces would be like when populated, for example to understand how the mess looks when full of people having a meal or to evaluate sightlines to display screens for briefings.

This development process includes empirical testing of the design proposals. A full-sized prototype of the junior mess was evaluated with 25 people to understand how people used the seating and tables meals and sleep trials are underway to evaluate the consequences of different orientations of the berths in the boat of the berths and the effectiveness of the tapered sleeping berth configuration.

THE HCD PROCESS

The HCD process used for this project is based on the 'Design Double Diamond' developed by the UK Design Council (Design Council, 2007), Figure 1, and the principles from ISO 9241-210:2010 Ergonomics of Human-System Interaction -- Part 210: Human-centred design for interactive systems (International Standards Organisation, 2010). This process is used for a variety of projects including user interface, user experience, service design as well as product design. Note, ISO 9241-210:2010 is part of the standard for Human Factors Integration ISO/TS 18152, the human systems model in ISO/TS 18152 conforms to and extends ISO 9241-210. This project focused on HCD methods and practices and so references ISO 9241-210 in preference to the broader ISO/TS 18152.

There are several ways the HCD process is described, they share similar characteristics, stages and structures but use different formats and representations to emphasize different aspects of the process. The Double Diamond was used for this project as it provides a simple and well-established format. It has four stages, Develop (divergent research), Define (convergent clarification), Develop (divergent ideation) and finally Define (convergent implementation). The use of HCD for ship design is being developed whereby user engagement, field research and collaborative practices are being used to develop bridges and ships engine rooms (Gernez, et al., 2018).

The Double Diamond can be mapped onto the system engineering lifecycle V-model used for managing the overall development process, The Discover and Define stages are analogous to 'developing the concept of operations' and 'systems level requirements' from the V-model and Develop and Deliver correspond to the 'sub-systems requirements' and 'detailed design' from the V-model. The Double Diamond process operates in conjunction with the main V-model process but independently to suit the flexible approach required for user engagement.

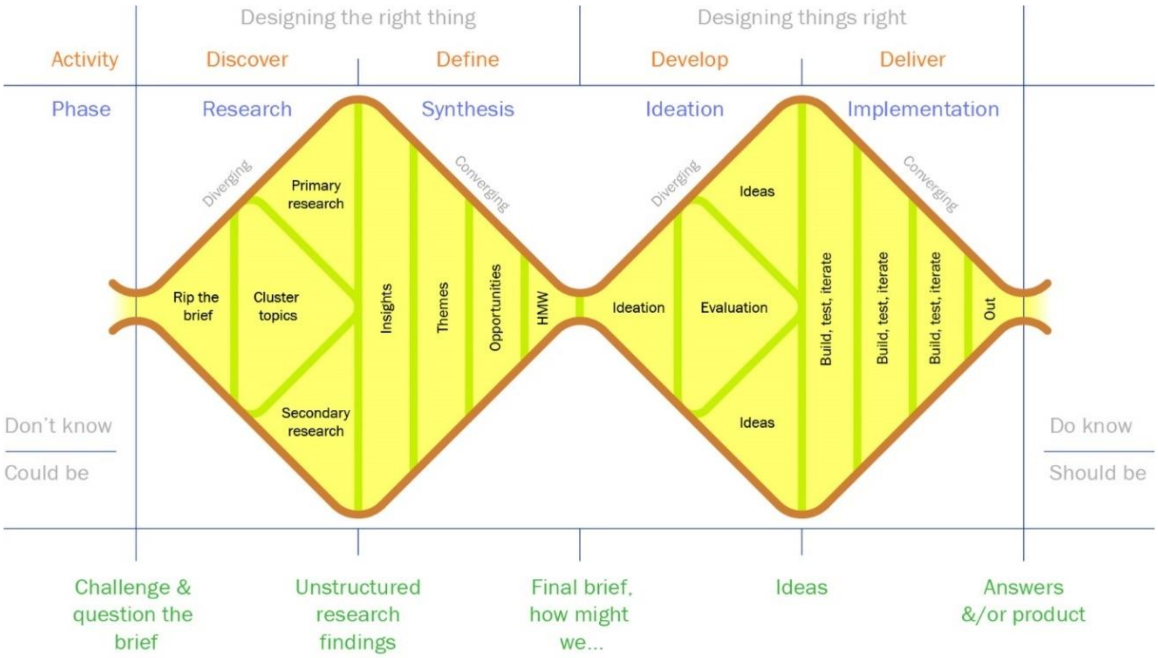

Figure 1 - The Design Double Diamond.

These HCD principles from ISO 9241-210:2010 are:

- The design is based on an explicit understanding of users, tasks and environments. Submarines are unusual environments that need to be investigated to ensure the design team understands the context and the user needs.
- Users are involved throughout the design and development process. Submariners are the best source of information about the activities and challenges that come with life on board submarines.
- User feedback is a critical source of information. Designs were evaluated with users and their feedback was used as the basis for improvements to the design.
- The process is iterative. Iteration involves repeating design cycles until the design satisfies the users' needs, iteration enables the progressive elimination of uncertainty and risk.
- The design addressees the whole user experience. HCD addresses ease of use as well as social, psychological, fatigue and emotional aspects.

- The design team includes multidisciplinary skills and perspectives. A strong HCD team includes a diverse range of skills and knowledge including industrial design, human factors, engineering, anthropometry and psychology.

The different stages of the HCD process used different methods. The first two stages, Discover and Define, dealt with understanding and documenting the user's needs. The user needs were then used as the basis of the design development in the Develop and Deliver stages. The following sections describe each stage and how they were implemented for the submarine habitable space exemplar designs.

Discover (Divergent Research)

This is the stage where the design team conducted research to understand the users and the context. A core method at this stage were workshops with submariners to understand their goals, activities, issues with the current platform and their requirements for future vessels. Other methods used at this stage included site visits, a literature and standards review, a technology search and an investigation of similar environments such as space habitation, aircraft and submarines used by other navies. This stage produced a large amount of qualitative information that was analysed and synthesised in the next stage.

Define (Convergent Clarification)

This stage focused on synthesizing and bringing structure to the findings of the Discovery stage in order to develop criteria, use scenarios and ergonomic and technology hard-points. It drew together the wide array of qualitative and dimensional information and presented it in a format to provide focus for the design development and evaluation stages. The data qualitative was analysed using methods from the social sciences and anthropology, such as affinity diagramming, to reveal patterns and insights. Diagrams were created to show the ergonomic hard-points, work-flows, spatial relations between components, functions and user needs.

Develop (Divergent Ideation)

This stage created several design proposals based on the hard points, scenarios and criteria from the Discover and Define stages, the designs were evaluated with users and developed iteratively. CAD models and physical prototypes were made to elicit feedback and responses from users. The human fit was continually evaluated using the DHMs in CAD and with the use of physical prototypes.

Submariners were consulted in workshops where illustrations, VR and physical models were used to communicate the proposals. The user workshops were held regularly as part of an iterative process to ensure the design proposal met the user needs.

The user workshops were summarised in reports that described the design development process, the workshop activities and the user feedback. These reports provided the evidence base for the final design proposal.

Define (Convergent Implementation)

This stage refined the design based on the input of the submariners. The human fit was evaluated with the DHM simulation software Jack™. The design proposal was documented and described explaining the design with reference to the user needs, criteria, use scenarios, anthropometry and technical constraints.

EXEMPLAR PROJECTS

Several design exemplars were developed for this project, the sleeping berth and cabin, the junior and senior sailors mess, wardroom and galley. These areas were identified by the DSTG as problematic on the Collins Class and requiring attention for future submarines (Ponton & Parera, 2015). The spaces were developed in isolation from the general arrangement.

User Engagement Activities

At the core of the HCD process was user engagement at all stages of the project, from the initial 'Discovery' stage through to the evaluation of design proposals in the 'Develop' stage. The following tables, Tables 1 and 2, show the user workshops conducted over the course of the project. These workshops involved 8 to 10 submariners which gave the group diversity in ranks, roles and experience. The participants were different for each workshop, except for the two iterations of the mess and galley development that used the same participants.

In addition, there were numerous informal conversations, boat tours and demonstrations with submariners that provided background information and enabled the design team to gather feedback on workshop outcomes and design proposals. The iterative nature of the workshops enabled the progressive elimination of uncertainty and risk and confidence the outcome would meet the users needs.

A trial of the junior mess prototype was conducted using 25 non-submariners to evaluate how people sit and eat meals in the space and to evaluate how the design supported other activities including recreation, damage control and triage.

Table 1 - Sleeping berth and cabin - user engagement activities

Stage / Date	Discovery: 29th – 31st May 2017	Develop: 20th – 21st February 2018
Duration	2 ½ days (6 hours / day)	2 days (6 hours / day)
Participants	8	10
Activities	Guided boat tour Focus group Co-design development with full scale physical models Affinity diagramming	Review of criteria Review of berth options Review of storage requirements Berth access and egress evaluation Evaluation of the cabin in VR

Table 2 - Mess and galley - user engagement activities

Stage / Date	Discovery: 7th – 8th June 2018	Develop Iteration 1: 28th -29th November 2018	Develop Iteration 2: 5th – 6th March 2019	Evaluation: 15th April 2019
Duration	2 days (6 hours / day)	2 days (6 hours / day)	2 days (6 hours / day)	1 day (6 hours / day)
Participants	8 submariners including 2 cooks	8 submariners including 2 cooks	8 submariners including 2 cooks	25 participants (no submariners)
Activities	Workshop on use scenarios Co-design development with full scale physical models	Review of design proposals, scenarios and criteria, with VR and illustrations	Review of full-sized physical mock-ups	Simulation of junior mess use scenarios in a full-sized mock up

RESULTS AND DISCUSSION

The outcome of this project was an HCD process and methods integrated with anthropometric design and assessment tools tailored to the task of developing habitable spaces on submarines. This process was used to develop a set of design concepts for the sleeping berths / cabin and the mess and galley for future submarines in order to demonstrate the HCD methods and to develop criteria and use scenarios for design assurance.

By taking a human centred approach, engaging with users at all project stages, applying anthropometry and implementing psychological and physiological considerations into the design the submariner's opportunity for effective rest is potentially improved resulting in better cognitive performance and decision making. This has implications for reducing fatigue, improving crew endurance and enhancing cognitive performance and decision making, giving operators a combat edge.

Working closely with submariners at all stages of the process provided confidence that the design is fit for purpose as well as appealing and comfortable which has implications for recruitment and retention.

Using DHMs and the anthropometric data at all stages of the process provides assurance that the final design will be sized to fit the range of body sizes in the RAN population.

The use of physical prototyping was vital for the development of the designs and for the user engagement. VR was also an important tool for design development and user engagement as it enabled designers and users to experience a variety of design proposals early in the process and provide feedback before physical prototypes were constructed.

Sleeping Berths and Cabins

For the purposes of this exercise a longitudinally orientated berth on the mid-deck in a cabin of six was used as the basis for the design. The berth and cabin, Figure 2, includes the following features:

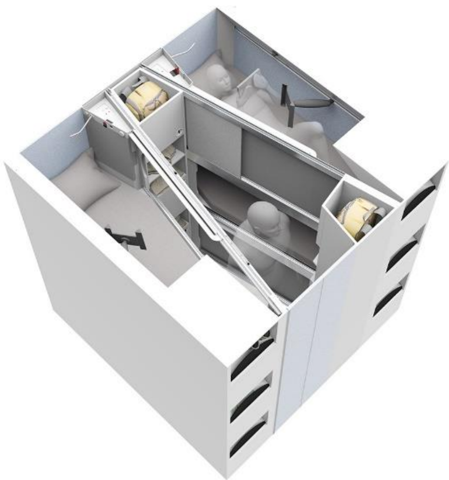

Figure 2 - The sleeping berth and cabin proposal showing the tapered berth and cabin space.

- A tapered berth and cabin to provides more room around the upper body in the berth and more space in the cabin. The berth is wider across the shoulders where people's bodies are at their widest and where most activity occurs, and narrower at the feet where less space is required. This uses the space more efficiently and makes the volumes appear larger. The tapered configuration was met with high approval from the submariners.
- A sliding panel at the head end of the berth was included to block out sound and light. A curtain was used for the remainder of the enclosure at the knees and feet for ease of egress, to reduce the perception of confinement and to allow for air movement.

- A variety of lighting options were developed to suit the various use scenarios. For example, the cabin has a bright light for use when in port while people are moving in and stowing their belongings and there is a dim red light for use when underway so that people can see what is in the cabin without disturbing others who are asleep.
- The lighting has different colours to match the occupant's circadian rhythm. The lights in the berth are set at 2000-3000^{0}K (red/orange) in the evening to assist with the transition to sleep and they set are at 6000^{0}K (daylight) in the morning to assist with the transition from sleep to work.
- A range of air-conditioning outlets allow the users tailor the air location and flow according to their preferences.
- Keeping bath towels and boots dry is an important factor for comfort, hygiene and odour reduction. The proposal includes a ventilated bay where towels and boots can be dried and stored.
- Lockable storage space is provided in the cabin for uniforms and larger items, in addition there is storage inside the berths for personal items with a power outlet for charging devices. The storage includes loops for tying down items so they don't shift and rattle as the boat moves.

Mess

The mess, Figure 3, includes the following features:

Figure 3 - The junior sailor's mess.

- An arrangement that allows for a range of use scenarios including meals, recreation, briefing, damage control and triage.
- The tables are arranged to reduce the amount of people that are 'sat-in' and unable to leave the table without asking others to move. The tables can be modified to make longer tables so people can be laid down for first aid and medical care.
- Three TV screens are arranged so everyone has a good line of sight for presentations and entertainment.
- A sideboard includes a drinks station, fridge and bin with space for the entertainment equipment and media.
- The banquette seating around the periphery allows for flexible seating arrangements as well as providing for a good amount of storage underneath the seats. The peripheral seating minimises the number of people with their back to the group so that people can see other people's faces in order to support social cohesion.

Galley

The galley, Figure 4, includes the following features:

- The space for appliances is configured for maximum flexibility and so appliances can be changed out as technology changes.

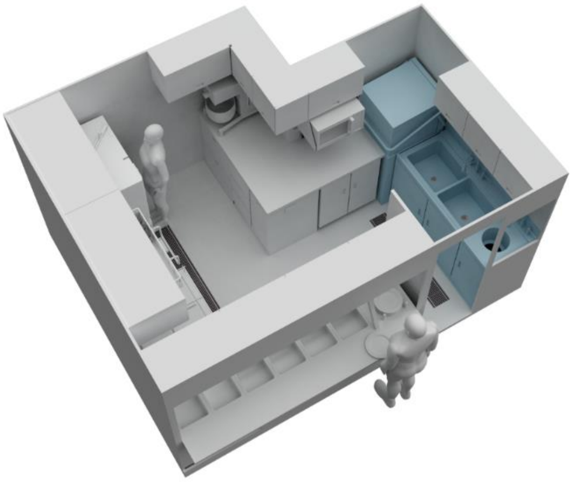

Figure 4 - The galley proposal showing the area designated for the dishwashing tasks.

- The arrangement accommodates the dishwashing, food preparation, cooking and serving activities in different zones within the galley for effective workflows and to avoid cross contamination of raw and cooked food.
- A servery for six standard 1/1 gastronorm trays is included so that a range of meal options can be provided.
- Storage is provided for utensils, standard gastronorm cooking trays, cleaning chemicals and food staples.
- Dishwashing takes place in a small zone separate from the food preparation zones. There is a linear workflow starting where the plates are deposited, scraped, then washed before being returned to storage.

ASSUNARNCE PROCESS

The assurance process developed as part of the project has been used to evaluate alternate design proposals using these scenarios, criteria and design exemplars as the basis of the evaluation. This provided the framework for comparing different design arrangements, defining the trade space and describing the advantages and trade-offs of various proposals. This outcome was a detailed, user centred evaluation that provided the client with a rich and detailed analysis inform the decision-making process.

FUTURE WORK

The work conducted to date demonstrates how the HCD process and methods can be implemented for the design of submarine habitable spaces. Elements of the designs will be tested empirically in an experimental environment to quantify cognitive and physiological benefits and the impact on fatigue and subsequently operational effectiveness. The relationship between improved habitability and crew recruitment and retention can be explored comparing the design proposals to the exiting accommodation on the Collins Class submarines.

CONCLUSIONS

The project resulted in the application of the HCD process for submarine habitable spaces that focuses on close engagement with users throughout the process, applied anthropometry and the consideration of the psychological and physiological dynamics. The HCD process is described in the existing ergonomics standards, what is novel is implementing it in an integrated way early in the process where it can have the greatest impact.

The outcomes of this project are innovative submarine habitable space design proposals and criteria and use scenarios for use in design assurance. It uses creative methods and a rigorous, transparent approach that has be applied to the mess/galley, sleeping berths and control room. This approach can also be applied to other areas such as the exercise areas, ablutions, and for maintenance access and usability.

REFERENCES

Banks, S. (2007). Behavioral and physiological consequences of sleep restriction. *Journal of clinical sleep medicine*, *3*(05), 519-528. Beyer, H., & Holtzblatt, K. (1997). *Contextual design: defining customer-centered systems*. Elsevier.

Council, D. (2007). Eleven lessons: Managing design in eleven global companies-desk research report. *Design Council*.

Chief of Naval Operations. (1996). OPNAVINST 9640.1A, Shipboard Habitability Program. Retrieved from http://neds.daps.dla.mil/Directives/table34.html

Gernez, E., Nordby, K., Seim, Ø., Brett, P. O., & Hauge, R. (2018). Human-centered, collaborative, field-driven design—a case study. In Marine Design XIII, Volume 1 (pp. 291-305). CRC Press.

International Standards Organisation. (2010) Ergonomics of human-system interaction -- Part 210: Human-centred design for interactive systems (ISO 9241-210:2010). Retrieved from http://iso.org

International Standards Organisation. (2010) Ergonomics of human-system interaction – Specification for the process assessment of human-system issues (ISO/TR 18152). Retrieved from http://iso.org

Miller, N. L., Matsangas, P., & Shattuck, L. G. (2008). Fatigue and its effect on performance in military environments. *Performance under stress*, *2007*, 231-49.

Nebes, R. D., Buysse, D. J., Halligan, E. M., Houck, P. R., & Monk, T. H. (2009). Self-reported sleep quality predicts poor cognitive performance in healthy older adults. *The Journals of Gerontology: Series B*, *64*(2), 180-187.

Ponton, K. (2019). A Revised *Maritime Physical Accommodation Guidance for the Royal Australian Navy.* DSTG.

Ponton, K., & Parera, D. (2015). *The Submarine Habitability Assessment Questionnaire SUB-HAQ: A Survey of RAN Submariners.* DSTG.

Ponton, K., Gamble, D., Coleman, J., Furnell, A., Sockshell, S., Fletcher K. (2019) *Revised Anthropometry Guidance for the Royal Australian Navy.* DSTG.

Schwerin, M. J., Kline, T. L., Olmsted, M. G., & Wilcove, G. L. (2006). Validation of a work/non-work life model of quality of life and retention among Navy personnel. Paper presented at the Center for Naval Analysis Workforce Research Conference, Falls Church, VA.

Shay, J. (1998). Ethical standing for commander self-care: the need for sleep. *Parameters, 28*(2), 93.

Wilcove, G. L., & Schwerin, M. J. (2008). Shipboard habitability in the US Navy. *Military psychology*, 20(2), 115-133.

Shobe, K., Bing, M., Duplessis, C. L., Dyche, J., Fothergill, D., Horn, W., . . . Plott, C. (2003). *Psychological, Physiological, And Medical Impact Of The Submarine Environment On Submariners With Application To Virginia Class Submarines - Technical Report #TR-1229*.