Research Requirements for Modelling of Auditory Communication in Critical Control Spaces on RCN Platforms

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Abstract

Research on layout optimization is being conducted in the interest of improving performance in critical control spaces on future Royal Canadian Navy (RCN) platforms. Previous algorithms for layout optimization have not adequately addressed the acoustical environment and its effects on speech communication. This report aims at filling the gap in knowledge by 1) reviewing previous work on auditory communication onboard RCN platforms, 2) summarizing current standards for speech communication, and 3) summarizing the effects of the acoustical environment and room acoustics modelling. These literature review findings are combined with observations from a tour of the critical control spaces in a Halifax Class Frigate to identify short-term solutions (data collection and modelling) for improving the modelling of auditory communication in layout optimization. Finally, future experiments, human factors analyses, and modelling for optimizing communication performance are proposed.

Significance to defence and security

Effective communication within the critical control spaces on RCN platforms is critical to mission success. This work identifies the key elements that that hinder communication and how they can be addressed within an optimized workspace layout.

Résumé

Des recherches sont en cours sur l’optimisation de l’aménagement des espaces de contrôle essentiels afin d’améliorer leur efficacité sur les plateformes futures de la Marine royale canadienne (MRC). Jusqu’à maintenant, les algorithmes d’optimisation n’ont pas tenu compte de manière adéquate du milieu acoustique ni de ses effets sur la communication verbale. Le présent rapport vise à combler cette lacune au chapitre des connaissances. On y aborde les éléments suivants : 1) revue des travaux antérieurs réalisés en matière de communication auditive à bord des plateformes de la MRC, 2) résumé des normes actuelles de la communication verbale, 3) résumé des effets du milieu acoustique et de la modélisation de l’acoustique des salles. Les conclusions tirées de cette étude documentaire et les observations notées lors d’une visite des espaces de contrôle essentiels d’une frégate de classe *Halifax* permettent d’élaborer des solutions à court terme (collecte de données et modélisation) pour améliorer la modélisation de la communication auditive en vue d’optimiser l’aménagement. Finalement, des projets d’expériences, d’analyses des facteurs humains et de modélisation pour l’optimisation des communications sont proposés.

Importance pour la défense et la sécurité

L’efficacité des communications dans les espaces de contrôle essentiels des plateformes de la MRC joue un rôle crucial dans le succès de toute mission. Les travaux présentés ici cernent les principaux éléments qui entravent les communications et la manière de les aborder dans l’aménagement d’un espace de travail optimisé. L’efficacité des communications dans les espaces de contrôle essentiels des plateformes de la MRC joue un rôle crucial dans le succès de toute mission. Les travaux présentés ici cernent les principaux éléments qui entravent les communications et la manière de les aborder dans l’aménagement d’un espace de travail optimisé.

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1 Introduction

The Royal Canadian Navy (RCN) crewing and human factors project is focussed on 1) providing timely advice and analyses through scientific methods to determine crewing requirements for current and future RCN platforms, and 2) investigating and addressing human factors issues as they relate to critical control spaces, human performance, human interaction with advanced automation and habitability onboard future naval platforms. One component of human factors for critical control spaces includes layout design, evaluation and optimisation. The objective of this component is to provide the RCN with a standard methodology and a supporting toolset for evaluating proposed layout designs of critical control spaces on naval platforms. A critical factor to be considered in layout design is whether or not the workspace facilitates effective communication. Auditory communication is affected by the presence of background noise and competing auditory channels (e.g., multiple talkers or radio channels and auditory alerts), which could lead to auditory overload. The acoustical properties of the room (e.g., shape, size, reverberation, location of noise sources) dictate how sounds, including speech, propagate in the workspace. To date, the acoustical environment and its implications on speech communication have not been adequately considered in the modelling of workspaces on RCN platforms. This report will: 1) review previous work on workspace layout modelling, noise surveys and communication onboard RCN platforms, 2) review the effects of noise on speech communication and relevant standards, 3) briefly describe modelling of the acoustical environment (room acoustics), which has a direct effect on speech and noise, 4) summarize observations from an RCN frigate visit relating to auditory communication, and 5) present recommendations for improving the modelling of auditory communication and future research.

2 Previous work on auditory communication onboard RCN platforms

2.1 Workspace layout modelling

There have been few known studies of workspace layout modelling in naval environments. Previous work has used LOCATE, a computer-aided workspace layout program that includes the modelling of human-machine and human-human communication (Hendy, 1984). It has been used in naval environments to model communication on the bridge (Hendy et al., 1989) and in the operations room (ops room; Edwards, 2003) of RCN surface vessels. For modelling of the bridge, a largely qualitative assessment of auditory communications quality was used. A link strength function was developed based on the talker-listener distance at a fixed background noise level. For distances beyond two metres, a sharp cut-off in the function was applied. The speech source was assumed to be omnidirectional, meaning that the talker always faces the listener. The speech propagation was assumed to be unaffected by obstructions in the room (Hendy et al., 1989). In the analysis of the ops room, very few details about the auditory link strength function were given. Auditory communication was assumed to be of high quality because headsets were used (Edwards, 2003). The simplistic treatment of auditory communication in previous studies demonstrates a gap in knowledge that should be addressed in future layout modelling efforts.

2.2 Noise surveys

Noise surveys provide important information about the acoustical environment. To the authors' knowledge, only one noise evaluation onboard RCN platforms has been reported. A relatively high incidence of noise-induced hearing loss in sea-element trade categories prompted a noise survey of the HMCS Iroquois (Crabtree, 1975). Noise data was collected at sea in the critical control spaces, engine rooms and living spaces (including sleeping areas). In the ops room, the differences in the overall noise levels during quiescent and operational times (anti-aircraft and submarine training exercises) were 1 dB or less. This is a just-noticeable difference in sound intensity based on controlled laboratory studies (Berger et al., 2003), but is likely insignificant in an operational setting. It was noted that the highest noise levels were close to the air conditioning unit. This suggests that Heating-Ventilation-Air Conditioning (HVAC) and machinery noise rather than voice communication are the main contributors to the overall noise levels. The overall A-weighted noise levels ranged from 69 to 78 dBA throughout the room[1]. The bridge was the least noisy of all the operational areas at 64 dBA, which was said to be acceptable for face-to-face speech communication up to six feet; this information was used in the bridge activity analysis by Hendy et al. (1989). Crabtree's report concluded that the ambient noise levels should not affect operations, as long as noise-attenuating headsets were worn in the noisier areas such as the engine rooms. There were, however, concerns about the noise levels in the living/sleeping areas from a

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[1] Background noise levels are often reported as A-weighted values. The A-weighting is a frequency weighting curve defined by the American National Standards Institute / Acoustical Society of America (ANSI/ASA) S1.4-1983(R2006) and the International Electrotechnical Commission (IEC) 61672-1:2013, designed to approximate the response of the human auditory system.

habitability standpoint (Crabtree, 1975). Noise surveys should be included in the analysis for workspaces.

2.3 Communication analyses

It is important to consider the different methods of auditory communication that are used in a given environment and their interactions. The acoustical environment particularly has implications for operators who are (or should be) co-located due to frequent voice communication. A Hierarchical Goal Analysis (HGA) of the Canadian Patrol Frigate (CPF) ops room suggested that the majority of the feedback requirements were addressed verbally (i.e., using the auditory channel), which could overload the auditory channel (Chow et al., 2007). The analysis did not distinguish between face-to-face auditory communication and communication via headsets, and there was no direct examination of interactions or interference (if any) between these two forms of auditory communication. The use of visual aids could help to reduce the auditory workload. For example, previous work has been done on optimization of alerts (audio, visual and audiovisual) in the ops room (Nakashima and Crebolder, 2010; Crebolder, 2012). Analyses of auditory communication should distinguish between the different methods of voice communication (e.g., radio versus face-to-face) and consider the interaction of non-verbal auditory interferences such background noise and alerts.

The shortcomings of the previous studies indicate a lack of knowledge with respect to speech communication in noise. The next chapter presents an overview of current standards for speech communication.

3 Effects of noise: Standards for speech communication

When considering the effects of the environment and background noise on speech communication, it is important to understand the acoustical properties of human speech. Human speech is broadband, peaking at about 500 Hz and falling off with increasing frequency until about 4000 Hz. Male and female voices are similar in spectral content from 250 to 5000Hz, but differ at frequencies below 200 Hz due to the lower fundamental frequency of the male voice. Human speech spectra have been found to be remarkably similar over 12 different languages (Byrne et al., 1994). Speech levels are influenced by a number of factors, including separation distance, orientation of the speaker, individual differences and background noise (Bronkhorst, 2000). The amount of speech interference caused by background noise depends primarily on the signal-to-noise ratio (SNR) at speech frequencies. There are several standards relating to speech and the design of auditory displays that are relevant to speech communication in workspaces. The American National Standard Institution / Acoustical Society of America (ANSI/ASA) standard S12.65:2006(R2011) describes a metric for rating the background noise, called the Speech Interference Level (SIL). The Speech Intelligibility Index (SII), which quantifies the percentage of speech cues that reach the listener in a room, is described in ANSI/ASA S3.5-1997(R2012). Methods for designing and testing communication systems are described in ANSI/ASA S3.2 and Military Standard (MIL-STD) 1472G.

3.1 Speech Interference Level (SIL)

ANSI/ASA S12.65:2006(R2011) describes a method for rating noise with respect to speech interference, for face-to-face communication (i.e., not electronically transmitted). The speech interference level (SIL) for a given background noise is defined as being one-fourth the sum of the sound pressure levels measured in octave bands 500, 1000, 2000 and 4000 Hz; these sound frequencies are important for speech understanding (ANSI/ASA, 2006). Figure 1 shows the separation distance between a talker and a listener as a function of the SIL in decibels. Also shown below the abscissa is the approximate A-weighted level for common background noises; the actual relationship between the SIL and the A-weighted level depends on the spectrum of the noise in question. The SIL is given for four levels of speech effort: normal, raised, very loud and shout. The figure indicates the separation distance in metres for just-reliable communication. Just-reliable communication is described as having an expected score of 70% on a speech intelligibility test using monosyllabic words. The expected voice level reflects the tendency to speak louder in the presence of background noise; this is known as the Lombard effect (Lane and Tranel, 1971). It is noted in ANSI S12.65 that the SIL does not account for lip reading and therefore overestimates the voice levels required for listeners who benefit from such visual cues.

According to Crabtree (1975), the noise levels in the destroyer ops room ranged from 68 to 75 dBA. Using the SIL shown in Figure 1, at 68 dBA, the talker would have to speak at a “raised” level (SIL = 60 dB) to be heard at a distance of 2m. At 75 dBA, the talker would have to speak at a “very loud” level (SIL = 66 dB) to be heard at 2m.

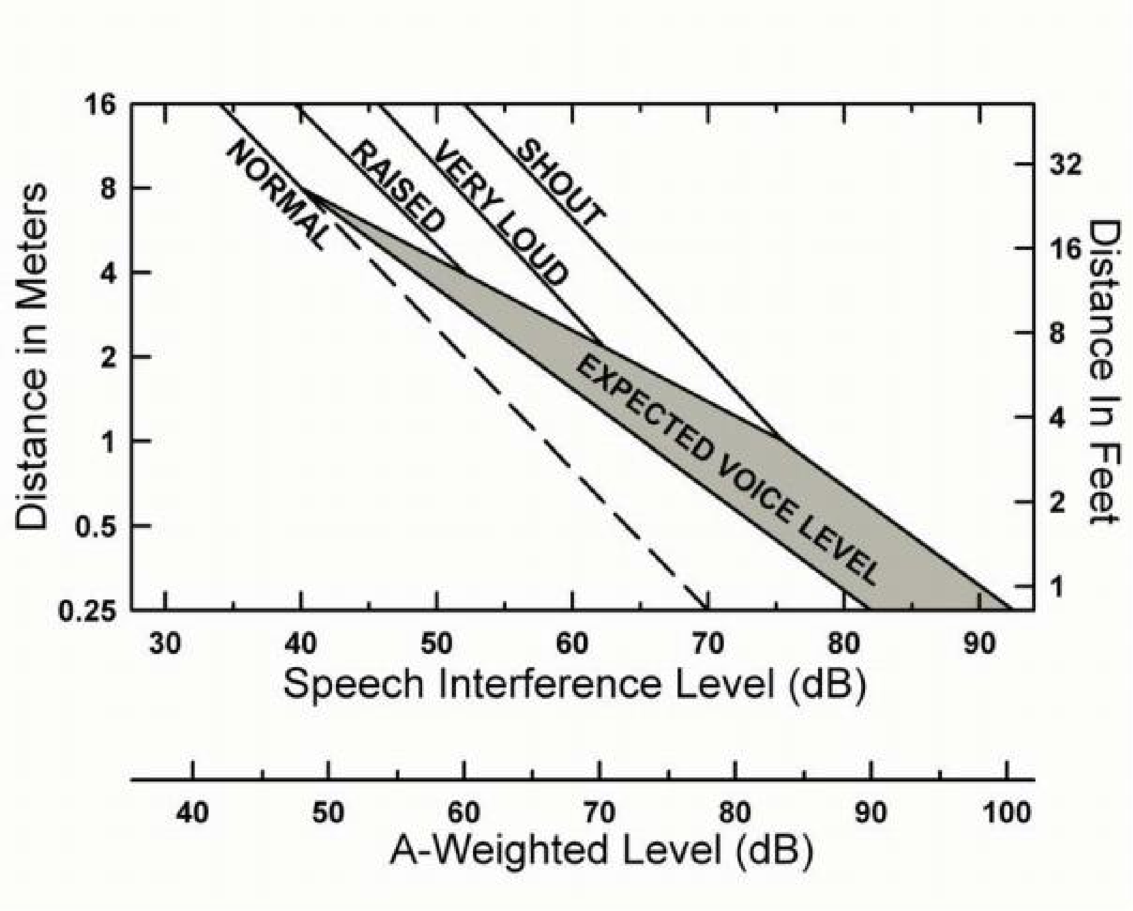

Figure 1: *Speech interference level (SIL) reprinted from ANSI/ASA S12.65:2006(R2011), Figure 1. The original caption reads: "The region below each curve shows the talker-to-listener and noise-level combination for which just-reliable face-to face communication is possible. The parameter on each curve indicates the relative voice level. The A-weighted sound level shown below the abscissa is approximate. The relation between speech interference level and A-weighted sound level depends on the spectrum of the noise."*[2].

3.2 Speech Intelligibility Index (SII)

ANSI/ASA S3.5-1997(R2012) describes methods for calculation of the Speech Intelligibility Index (SII) based on the spectrum levels of the speech and background noise, reverberation of the room and vocal effort. The SII ranges from 0.0 (no speech cues reach the listener) to 1.0 (all speech cues reach the listener). The calculation of the SII can be extended to listeners with hearing loss. Use of the SII provides more information than the SIL given that it provides a range of speech intelligibility rather than a binary response (just-reliable or not) but more information is

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[2] Reprinted from ANSI/ASA S12.65:2006 (R 2011) *American National Standard for Rating Noise with Respect to Speech Interference*, © 2006, with the permission of the Acoustical Society of America, 1305 Walt Whitman Road, Suite 300, Melville, NY 11747.

required for its use. In particular, calculation of the SII requires the spectrum of speech and noise with a minimum resolution of octave bands, as well as the hearing thresholds of the listener. Suggested methods for measuring these values are provided in the standard. By contrast, determination of the SIL requires only a single value, the A-weighted background noise level. The SIL and SII are metrics that can be calculated from physical measurements and can realistically be used in the context of the current work. Future work could consider perceptual and cognitive aspects of speech understanding in noise.

3.3 Communication systems

To evaluate the intelligibility of speech over communication systems (e.g., telephones, broadcast systems, communication headsets), ANSI/ASA S3.2-2009 describes the conduct of specific tests: the Phonetically Balanced (PB) monosyllabic word test, the Modified Rhyme Test (MRT) and the Diagnostic Rhyme Test (DRT). The outcome measure of these tests is the percentage of correctly identified words by the listener. A score of 70% meets the requirement for "just reliable" communication used in ANSI/ASA S12.65. The standard requires that the selected speech test be conducted with pairs of participants, using a minimum of five talkers and five listeners. The sessions are conducted such that each of the talkers is paired with each of the listeners (e.g., if using 5 participants that act as both a talker and a listener in different sessions, a minimum of 20 sessions must be conducted). With the number of different communication pathways and operational scenarios that are possible in the various control spaces of the frigates, application of ANSI/ASA S3.2 would be an onerous task. If the most critical or frequently used communication pathways could be identified, e.g., possibly between the Officer of the Watch and the Helmsman on the bridge, or possibly between the Operations Room Officer and the Above Water Warfare Director in the ops room, priority could be placed on these scenarios for testing.

Requirements for the design and use of communication systems, auditory displays, and auditory alerts are given in MIL-STD 1472G (2012). The standard includes guidelines for the use of hearing protection, maximum output levels for communication systems, maximum ambient noise levels for face-to-face communication and presentation levels for auditory alerts. The standard references ANSI/ASA S3.2 and stipulates the use of the MRT for testing communication systems. A table of maximum permissible and preferred noise levels for ships and maritime structures is given in Table 28 of MIL-STD 1472G. The indicated noise levels likely account for both communication requirements and noise exposure safety. For example, the preferred and maximum noise limits for the navigation bridge are 55 and 65 dBA, respectively. The noise limits for fan rooms where likely little to no communication takes place are 84 (preferred) and 100 dBA (maximum).

Of the standards described above, ANSI/ASA S12.65 (based on SIL) is likely the easiest to integrate into LOCATE or comparable software. The background noise levels at the talker and listener positions can be used to calculate the SIL, and this information can be used to modulate the link strength function for auditory communication. To improve the accuracy, it would be helpful to have noise levels at each of the workstations rather than just one value for the whole room. Link strengths could possibly be reduced if the listener is located close to a noise source such as an HVAC outlet, or if they are in a selective listening situation dealing with competing messages (Bronkhorst, 2000; Brungart et al., 2001). This would be in contrast to the sharp cut-off for the auditory channel used previously, which was based only on distance (Hendy et al., 1989).

However, if the SIL is to be used, the meaning of just-reliable communication must be considered (e.g., is 70% understanding of monosyllabic words acceptable in a critical control space?).

In the case of future RCN platforms, it is not possible to physically measure the noise background in spaces that have not yet been built. However, room acoustics models can predict the acoustical properties of well-defined rooms; these are described in the next chapter.

4 Effects of the environment: Room acoustics models

The physical environment influences the propagation of sound, and ultimately, the noise levels and discriminability of speech. Consider a highly reverberant environment, such as a squash court, and a non-reverberant environment such as a recording studio. Speech communication is more difficult in the squash court, which has a longer Reverberation Time (RT) than in the recording studio, which has a shorter RT. Critical control spaces on a CFP are likely between these two extremes and could be considered as semi-reverberant. There is a large amount of literature on room acoustics models as applied to industrial rooms, classrooms, concert halls, and other complex spaces. Two classical geometrical models that are frequently used in room acoustics software are the Ray Tracing Method and the Image Source Method. Briefly, in both models sound propagation is described by sound particles that are traced as they reflect off the surfaces of the room. Reflection off walls is treated according to the absorption coefficients that are assigned. The receiver point is treated as a volume. The smaller the receiver volume, the larger number of rays must be traced. In the image source model, specular reflections off walls are constructed geometrically by mirroring the source in the plane of the reflecting surface. Each model has benefits and drawbacks in terms of accuracy and computational time. Hybrid models that optimize the respective benefits of each model have been developed (Vorlander, 1989). Further details of both models have been presented by other authors (Kulowski, 1985, Allen and Berkley, 1979; Rindel, 2000). In addition to calculating values such as RT (ISO 3382, 1997) and sound pressure levels at a receiver position, computer models can be used to simulate the acoustics of the room through auralization. Auralization is achieved by digitally processing the acoustic response of the room (either measured or produced by a model) with a digital sound file such as speech or music. The resulting signal can be played back through headphones to present the virtual acoustical environment.

Software platforms for room acoustics are commercially available, and many are based on variations or combinations of ray-tracing and image-source models. Hodgson et al. (2008) compared the prediction results of two commercial models, ODEON (Horsholm, Denmark) and CATT-Acoustic (Gothenburg, Sweden), to measurements taken in two different classrooms with different reverberation and absorption characteristics. Predictions of RT and sound pressure level using both models were generally close to the measured results. Speech Intelligibility (SI) scores using auralized speech recordings were lower than the actual scores measured in the room with lower reverberation, confirming previous results. Generally, the two models were found to give equivalent results (Hodgson et al., 2008).

Successful use of room acoustics software requires careful `tuning` of the room. All surfaces of the room must be represented accurately using Computer-Aided Design (CAD) software, and the surface-absorption and diffusion coefficients for each surface must be chosen carefully to maximize the accuracy of the results. If the room is densely fitted (i.e., contains many objects such as machines, desks, benches, etc.), it becomes more difficult to model the acoustics (Hodgson, 1990). Two of the rooms of interest on the frigate will be described in the next section.

5 Preliminary analysis of critical control spaces

Several members of the research team participated in an informative tour of the HMCS Halifax on 6 November 2014. The tour included the following critical control spaces: the bridge, operations room, machinery control room, and communications control room. For consideration of acoustical modelling, only the bridge and the operations room are discussed here.

5.1 Bridge

The ship is navigated and steered from the bridge on deck 1. It is an enclosed space with one entrance from inside the ship and two doors exiting to the deck on the port and starboard sides. The interior surfaces (floors, walls and ceiling) of the bridge are covered in perforated metal, and there are windows of varying widths surrounding the perimeter of the bridge. There are seven or more seated workstations that are outfitted with multiple modes of communication: a telephone, an intercom speaker and a wired headset. In addition, there are three public address system loudspeakers: one above each of the exterior doors, and one in the ceiling (facing the floor) on the forward starboard side. There are several HVAC units and electrical panels that are potentially significant sources of noise. Some of these units are located above or very close to workstations. The workstations and other structures in the room (e.g., support pillars) present visual obstructions and reflecting surfaces that will affect auditory communication.

Discussions with the crewmembers indicated that the bridge is generally a quiet working environment. Noise levels will increase during action stations, but voice levels are controlled by the commanding officer. There are several external (communication with other ships and aircraft) and internal (communication within the ship) networks (nets) that are continuously monitored from the bridge. During missions, weapon firing or emergencies, there are many other nets that could be used. Up to four channels can be listened to concurrently on the headsets, although during quiet operations only two channels are typically used: air and ops room nets. The four channels are directed separately to the left ear, right ear, front and back, although it was indicated that the front and back channels are of limited functionality. The crew tend to move around the bridge and are more likely to use the telephone handsets rather than the headsets, unless air or weapon operations are being conducted.

5.2 Operations room

The ops room is the command and control centre of the ship. There are more than 20 seated workstations. There are many HVAC outlets, with several of them located directly above workstation seats. The workstations have headsets, intercom speakers and telephones for communication, as well as computer screens for text messages (chat). There are at least two public address system loudspeakers: one above the entry door and one on the forward port side. There might be another loudspeaker on the starboard side. Discussions with the crewmembers indicated that the crew are usually seated at their workstations and communicate through chat rather than through the headsets or face-to-face. Chat was estimated to be used for 80% of communication de-confliction.

Given the complexities of both rooms, it could be difficult to use acoustical modelling. Both rooms are densely fitted, contain many noise sources and many possible talker and receiver positions. In the bridge, the outside doors could be propped open, which further complicates the sound field. Face-to-face communication is common in the bridge, but the crewmembers are mobile and can move closer together to communicate when the background noise levels are high. In the ops room, since most of the communication is said to occur through headsets or chat, acoustical modelling for the purpose of predicting the SI would be of limited relevance. However, monitoring of multiple radio channels, particularly in the presence of high background noise, is a potential concern for auditory overload. It could be of interest to investigate the use of the headset auditory displays and chat for optimization of user performance. The results and recommendations of previous studies of auditory overload in multi-talker environments could be considered (Brungart et al., 2001; Abel et al., 2010, 2012, 2014, 2015).

6 Recommendations

6.1 Requirements for modelling

Because the intent of the layout optimization work is to improve the critical control spaces on future platforms, it would be interesting to use room acoustics software to create a virtual workspace. However, this would be resource intensive. While commercial room acoustics software models have been validated for other types of rooms, it is unknown if the results would be accurate for a critical control space at sea. Validation of the model would require an accurate representation of an existing room (e.g., an ops room or bridge) as input to the model and a room acoustics analysis of the room to compare to the model output. These tasks would have to be carried out by an expert in room acoustics modelling. DRDC does not have the software or sufficient experience to perform room acoustics modelling and validation, but does have contacts in academia and industry who could perform the work, if required. However, it is unclear how the output of such a model could be included in a layout design tool that is required to optimize many other performance criteria. If the SIL as described above can be incorporated as a simple input into a layout tool to represent auditory communication, complex and resource-intensive room acoustics modelling may not be required.

6.2 Requirements for noise surveys

The SIL has been identified as a possible first step to incorporate the effects of background noise of auditory communication. To the authors’ knowledge, there has been only one noise survey on an RCN platform (Crabtree, 1975). Therefore, it would be of interest to conduct a noise survey on a modernized CPF, with particular focus on the critical control spaces. The noise survey should be conducted at sea to enable data collection during a range of operations. Continuous recording of the noise levels, both overall and in 1/3 octave bands, should be conducted at various workstation positions in the bridge and ops room. The noise levels in other areas of interest, such as other control rooms and the engine room, could be intermittently monitored. Observations should be noted regarding the frequency and effectiveness of the various modes of communication. A survey should be administered to crewmembers to ascertain communication and auditory overload issues. Based on the previous noise data and discussions with the frigate crewmembers, it is expected that the noise levels in the critical control spaces could be high enough to affect face-to-face communication (i.e., raised or very loud voice levels required for short distances), but not high enough to warrant the use of hearing protection devices during normal operations. DRDC has the equipment and capability to perform an onboard noise survey and analyze the results. If concurrent noise recordings in multiple rooms were desired, additional equipment would be required.

6.3 Requirements for communication analyses

The SIL is useful for describing face-to-face communication between crewmembers who are co-located. However, other means of auditory communication have been identified for both co-located and distributed crewmembers: multi-channel radio headsets, telephones, intercom and public address systems. Although all of the methods have a common goal of communication through voice, they will be affected by background noise in different ways. For example, an increase in background noise will have a larger effect on face-to-face communication than radio communication if the radio headset is noise-reducing. The same increase in background noise could have a minimal effect on public address announcements if they are infrequently used. Human factors studies including questionnaires and field data collection could address the following under a range of operational scenarios: 1) the frequency of use for the different communication modes and their relative effectiveness, 2) which crew members are talking to each other and through which means, 3) the typical voice levels of the crew (normal, raised, very loud, shouting), and 4) the requirements for "just-reliable" communication (i.e., is 70% accuracy good enough?). This information could be used to tune the SIL (or similar metric) for communication between specific co-located or distributed operators.

The limitations of an individual to receive communications must also be considered. Attending to multiple radio channels and face-to-face communication in the presence of ambient noise can lead to auditory overload. It is well known that while humans can attend to a single talker among many (selective listening), they have difficulty attending to multiple concurrent talkers (divided listening); this "cocktail party" effect was demonstrated in an early study by Cherry (1953). Previous research on divided listening has been conducted by DRDC scientists in the context of an army mobile command post. In these experiments, participants listened and responded to target messages that were presented concurrently to the left and right ears through a headset and through an external loudspeaker. The use of visual alerts or text improved speech understanding and correct identification of target messages, and a slight advantage was observed for messages presented to the right ear (Abel et al., 2010, 2012, 2014, 2015). This work could be extended to RCN platforms to address the following research questions:

- What is the maximum number of radio channels that can be attended to without missing important messages?
- How can multiple radio channels be optimized to enhance detection of messages? (E.g., is there an operationally significant advantage for right ear vs left, or other virtual source positions?)
- How does attention to multiple radio channels affect the effectiveness of face-to-face communication, and vice versa?

For scenarios that are critical, frequent, or high risk, alternate designs of the critical control space may need to be considered (e.g., new layout, new communication technologies). DRDC has the scientific capability to conduct human experiments to evaluate the efficacy of these alternate designs. However, the feasibility of these human experiments will be limited by personnel availability (i.e., scientists and technologists to perform the research, and military participants for the experiments), and access to facilities (i.e., trainers or simulators that can be re-configured with proposed technologies, and made available for research experiments).

Initially, these research questions can be explored for normal-hearing, English-fluent crewmembers. However, it should not be assumed that the same level of performance can be achieved by individuals with a hearing impairment, or those who are not communicating in their native language. Two official languages and diversity within the Canadian Armed Forces account for some communications in non-native languages. Multinational operations may also involve communications in non-native languages with other navy personnel either face-to-face (e.g., a foreign exchange officer on a Canadian ship) or through headsets (e,g., on another ship within the Task Group).

6.4 Future work

It is clear that further research on communication performance and operational analyses are required to improve the modelling of auditory communication beyond the use of the SIL. The SIL considers background noise level, talker-to-listener distance, and vocal effort for face-to-face communication only. Background noise from machinery affects our ability to hear speech (energetic masking), but cross-talk from unattended conversations affects our ability to understand speech (informational masking). These two types of interference must be modeled in different ways. If the operators are locked into a headset, face-to-face communication must overcome the attenuation of the headset. The headset presents interference in addition to the noise. The experiments conducted to address the research questions listed above can help to identify the sources of communication interference. A complementary line of research is to explore how these sources of interference can be modeled.

DRDC has scientific capability to develop models of human performance, including how human operators interact with one another, and with various communication technologies (e.g., telephone handsets, radio headsets) within critical control spaces. These models can be integrated with existing and new speech interference models as discussed above to identify and to compare different communication scenarios (e.g., communicating face-to-face only with six operators; attending to two radio nets while communicating face-to-face with four operators; attending to four radio nets only) in terms of criticality, frequency, and risk. These new tools will enable more effective (i.e., evidence-based) and efficient (i.e., quickly comparing a large number of options) evaluations of proposed layout designs for critical control spaces.

7 Summary

We have identified four main points in this report:

- A first step to modelling the acoustical environment for communication (SIL);
- A need to collect relevant noise data to enable use of the SIL;
- A need to conduct human factors analyses and experiments on communication performance;
- A need to identify the operationally-relevant factors that interfere with communication for future modelling.

It is possible to improve the acoustical input into LOCATE (or future software) through use of the SIL, but noise surveys must be performed on modernized CPFs in order to obtain relevant noise data. Room acoustics models have not been validated for sea-going environments and would likely be too resource-intensive for practical use. In the interest of understanding the performance of crewmembers in terms of auditory communication, human factors analyses and experiments are required. Research on auditory overload could inform how the layout can be configured to optimize communication performance. Complementary research on modelling of communication interference could further improve the fidelity of a layout model and its applicability to a wide range of operational contexts.

References

[1] Abel, S.M., Nakashima, A., and Smith, I. (2010). Speech understanding in noise in the Bison Command, Control, Communications and Intelligence (Bison C3I) Mobile Command Post (MCP). DRDC – Toronto Research Centre, Technical Report, TR 2010-169.

[2] Abel, S.M., Nakashima, A. and Smith, I. (2012). Divided Listening in Noise in a Mock Up of a Military Command Post. Mil Med, 177(4):436–443.

[3] Abel, S.M., Ho, G., Nakashima, A. and Smith, I. (2014). Strategies to combat auditory overload during vehicular command and control. Mil Med, 179(9):1036–1042.

[4] Abel, S.M., Ho, G., Burrell, C.N. and Smith, I. (2015). The benefit of supplementary text for the resolution of auditory overload. DRDC – Toronto Research Centre, Scientific Report, DRDC-RDDC-2015-R066.

[5] Allen, J.B. and Berkley, D.A. (1979). Image method for efficiently simulating small-room acoustics. J. Acoust. Soc. Am., 65:943–950.

[6] ANSI/ASA S1.4-1983 (R2006). Specifications for sound level meters. American National Standards Institute, Standards Secretariat, Acoustical Society of America, Melville, NY.

[7] ANSI/ASA S3.2-2009 (2009).Method for measuring the intelligibility of speech over communication systems. American National Standards Institute, Standards Secretariat, Acoustical Society of America, Melville, NY.

[8] ANSI/ASA S3.5-1997(R2012) (1997).For calculation of the speech intelligibility index. American National Standards Institute, Standards Secretariat, Acoustical Society of America, Melville, NY.

[9] ANSI/ASA S12.65-2006(R2011). (2006). For rating noise with respect to speech interference. American National Standards Institute, Standards Secretariat, Acoustical Society of America, Melville, NY.

[10] Berger, E.H., Royster, L.H., Royster, J.D., et al., eds. (2003). The Noise Manual, revised 5th edition. American Industrial Hygiene Association.

[11] Bronkhorst, AW. (2000). The cocktail part phenomenon: A review of research on speech intelligibility in multiple-talker conditions. Acustica – acta acustica (86):117–128.

[12] Brungart, DS, Simpson, BD, Ericson, MA and Scott, KR. (2001). Informational and energetic masking effects in the perception of multiple simultaneous talkers. J. Acoust. Soc. Am. 110(2527):2527–2538.

[13] Byrne, D., Dillon, H., Tran, K., et al. (1994). An international comparison of long-term average speech spectra. J. Acoust. Soc. Am. 96(4):2108–2120.

[14] Cherry, E.C. (1953). Some experiments on the recognition of speech, with one and with two ears. J. Acoust. Soc. Am., 25(5):975–979.

[15] Chow, R, Crebolder, JM, Kobierski, RD and Coates, CE. (2007). Application of hierarchical goal analysis to the Halifax Class frigate operations room: A case study. DRDC – Toronto Research Centre, Technical Report, TR 2007-161.

[16] Crabtree, RB. (1975). A noise survey of the HMCS IROQUOIS. DCIEM Technical Report no. 76-X-26.

[17] Crebolder, JM. (2012). Investigating visual alerting in complex command and control environments. Journal of Human Performance in Extreme Environments: Vol. 10:Iss.1, Article 1.

[18] Edwards, JL. (2003). LOCATE analysis of Halifax Class frigate Ops room. DRDC – Toronto Research Centre, Contract Report, CR 2003-124.

[19] Hendy, KC. (1984). ‘LOCATE’: A program for computer-aided workspace design. Minor Thesis, Master of Engineering Science, Department of Electrical Engineering, Monash University, Melbourne, Australia.

[20] Hendy, KC, Berger, J and Wong, CC. (1989). Analysis of DDH280 bridge activity using a computer-aided workspace layout program (LOCATE). DCIEM No. 89-RR-18.

[21] Hodgson, M. (1990). On the accuracy of models for predicting sound propagation in fitted rooms. J Acoust Soc Am, 99(2):871–878.

[22] Hodgson, MR, York, N, Yang, W and Bliss, M. (2008). Comparison of predicted, measured and auralized sound fields with respect to speech intelligibility in classrooms using CATT-Acoustic and Odeon. Acta Acoustica United with Acustica, 94:883–890.

[23] IEC 61672-1:2013. (2013). Electroacoustics – Sound level meters – Part 1: Specifications. International Electrotechnical Commission, Geneva, Switzerland.

[24] ISO 3382 (1997). Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters. International Organization for Standardization, Geneva, Switzerland.

[25] Kulowski, A. (1985). Algorithmic representation of the ray tracing technique. Applied Acoustics, 18:449–469.

[26] Lane, H. and Tranel, B. (1971). The Lombard sign and the role of hearing in speech. Journal of speech, language, and hearing research, 14(4):677–709.

[27] MIL-STD 1472G. (2012). Department of Defence. Design criteria standard, Human Engineering.

[28] Nakashima, A and Crebolder, JM. (2010). Evaluation of audio and visual alerts during a divided attention task in noise. Canadian Acoustics 38(4):3–8.

[29] Rindel, J.H. (2000). The use of computer modelling in room acoustics. Journal of Vibroengineering, 3(4):219–224.

[30] Vorlander, M. (1989). Simulation of the transient and steady-state sound propagation in rooms using a new combined ray-tracing/image-source algorithm. J Acoust Soc Am 86(1):172–178.

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List of symbols/abbreviations/acronyms/initialisms

ANSI	American National Standards Institute
ASA	Acoustical Society of America
CAD	Computer-aided Design
CPF	Canadian Patrol Frigate
dBA	Decibels, A-weighted, sound pressure level
DRDC	Defence Research and Development Canada
DRT	Diagnostic Rhyme Test
HGA	Hierarchical Goal Analysis
HMCS	Her Majesty’s Canadian Ship
HVAC	Heating-ventilation-air Conditioning
Hz	Hertz, unit of sound frequency
MIL-STD	Military Standard
MRT	Modified Rhyme Test
PB	Phonetically Balanced monosyllabic word test
RCN	Royal Canadian Navy
RT	Reverberation Time
SI	Speech Intelligibility
SII	Speech Intelligibility Index
SIL	Speech Interference Level
SNR	Signal-to-Noise Ratio

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Research on layout optimization is being conducted in the interest of improving performance in critical control spaces on future Royal Canadian Navy (RCN) platforms. Previous algorithms for layout optimization have not adequately addressed the acoustical environment and its effects on speech communication. This report aims at filling the gap in knowledge by 1) reviewing previous work on auditory communication onboard RCN platforms, 2) summarizing current standards for speech communication, and 3) summarizing the effects of the acoustical environment and room acoustics modelling. These literature review findings are combined with observations from a tour of the critical control spaces in a Halifax Class Frigate to identify short-term solutions (data collection and modelling) for improving the modelling of auditory communication in layout optimization. Finally, future experiments, human factors analyses, and modelling for optimizing communication performance are proposed.

Des recherches sont en cours sur l'optimisation de l'aménagement des espaces de contrôle essentiels afin d'améliorer leur efficacité sur les plateformes futures de la Marine royale canadienne (MRC). Jusqu'à maintenant, les algorithmes d'optimisation n'ont pas tenu compte de manière adéquate du milieu acoustique ni de ses effets sur la communication verbale. Le présent rapport vise à combler cette lacune au chapitre des connaissances. On y aborde les éléments suivants : 1) revue des travaux antérieurs réalisés en matière de communication auditive à bord des plateformes de la MRC, 2) résumé des normes actuelles de la communication verbale, 3) résumé des effets du milieu acoustique et de la modélisation de l'acoustique des salles. Les conclusions tirées de cette étude documentaire et les observations notées lors d'une visite des espaces de contrôle essentiels d'une frégate de classe *Halifax* permettent d'élaborer des solutions à court terme (collecte de données et modélisation) pour améliorer la modélisation de la communication auditive en vue d'optimiser l'aménagement. Finalement, des projets d'expériences, d'analyses des facteurs humains et de modélisation pour l'optimisation des communications sont proposés.

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communication; acoustics; critical control space; Navy