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A review of display and input technologies for the development of the Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) decision aid system

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Abstract

The Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) is a decision aid system being developed by Defence Research and Development Canada (DRDC) – Atlantic Research Centre to revolutionize the way the Royal Canadian Navy (RCN) conducts Underwater Warfare (UWW). This Scientific Report outlines the high-level goals and requirements of the CRACCEN system and reviews several fields of research in order to determine the appropriate candidate technologies for which to develop the system. A variety of potential display and input hardware technologies are evaluated with regard to both task requirements and characteristics of the UWW task environment. The results of this review suggest that a tabletop display capable of accommodating a group of simultaneous users be adopted as the central display for the CRACCEN system, with the possibility of using additional displays and display modes to augment the capabilities of the UWW team. Further research with Subject Matter Experts (SMEs) is recommended to validate the viability, usability, and added value of these displays, and to iteratively design interfaces that are well-suited to both the display type and the needs of the CRACCEN users.

Significance to defence and security

The RCN has a long-term objective to revolutionize and modernize the conduct of UWW and the Command Reconnaissance Area Coordination and Control Environmental Network CRACCEN system will play a central role in this objective. In order for development and prototyping of the CRACCEN system to proceed, appropriate technologies need to be fitted to the demands of the tasks and the conditions of the task environment. This report reviews and analyzes various potential display and input technologies with regard to these requirements and provides concrete recommendations for prototype development and future research for eventual integration into CRACCEN.

Résumé

Le Centre de recherche de l'Atlantique de Recherche et développement pour la défense Canada (RDDC) élabore actuellement un réseau environnemental de coordination et de contrôle de la zone de reconnaissance du commandement (CRACCEN). Il s'agit d'un système d'aide à la décision visant à révolutionner la façon dont la Marine royale canadienne (MRC) mène la guerre sous-marine (GSM). Ce rapport scientifique énonce les objectifs et les exigences de haut niveau du système CRACCEN et examine plusieurs domaines de recherche afin de proposer des technologies envisageables qui conviennent à son élaboration. Le rapport évalue une variété d'écrans d'affichage et de technologies matérielles d'acquisition de données en ce qui a trait aux exigences opérationnelles de même qu'à l'environnement opérationnel de la GSM. Les résultats de cet examen indiquent que l'affichage central choisi du système CRACCEN pourrait être sous forme de surface de table. Cet affichage permet d'accueillir plusieurs utilisateurs simultanément et offre a possibilité d'utiliser des écrans et des modes d'affichages supplémentaires afin d'accroître les capacités de l'équipe de la GSM. Il est recommandé de poursuivre les recherches avec des experts pour vérifier la viabilité, la convivialité et la valeur ajoutée de ces écrans, ainsi que pour concevoir des interfaces de manière itérative qui conviennent au type d'écran d'affichage et aux besoins des utilisateurs du système CRACCEN.

Importance pour la défense et la sécurité

La MRC souhaite révolutionner et moderniser la conduite de la GSM, et le CRACCEN occupera une place centrale dans le cadre de cet objectif à long terme. Pour que le développement et le prototypage du système CRACCEN puissent aller de l'avant, les technologies appropriées doivent être adaptées aux exigences opérationnelles et aux conditions de l'environnement opérationnel. Ce rapport examine et analyse diverses technologies envisageables en matière d'affichage et d'acquisition de données en fonction de ces exigences et présente des recommandations concrètes concernant l'élaboration de prototypes et la recherche future aux fins d'une intégration ultérieure au système CRACCEN.

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1 Introduction

The Royal Canadian Navy (RCN) is invested in revolutionizing and modernizing the conduct of Underwater Warfare (UWW). The Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) project is a first step toward reaching this objective. Rather than providing incremental improvements to individual elements of the UWW system, the project aims to rethink existing Command and Control (C2) structures. Whereas the potential to supplant existing systems and structures with revolutionary new ones provides invaluable opportunities to streamline and improve UWW conduct, without being constrained by current systems, the open-ended nature of the project introduces new complexities.

Namely, the question of what such a revolutionary system should look like is left entirely open. Any number of existing, emerging, or future technologies for display and interaction might be applied to the problem to varying degrees of effectiveness. For development and prototyping of the CRACCEN system to proceed, the design space must be narrowed, and appropriate technologies must be selected. This Scientific Report reviews available display and input technologies with regard to the requirements of the tasks to be completed with the CRACCEN system and offers concrete recommendations for technology selection and future research.

1.1 Report outline

This report is organized as follows. Section 2 describes the CRACCEN project and system, and leverages previous work to define the system requirements that set the stage for the subsequent review and analysis. Section 3 discusses the methodological approach taken for this integrative review. Section 4 reviews the technologies that might be applied to the CRACCEN system. Section 5 evaluates the suitability of the technologies with regard to two types of constraints: the characteristics of the tasks to be accomplished by the UWW team using the CRACCEN system, and the conditions of the shipboard UWW task environment. Section 6 draws recommendations for display and input technology selection from the results of the integrative review, and outlines the future research required to validate and build upon the recommendations. Section 7 concludes the discussion of display and input technology selection for the CRACCEN system.

2 CRACCEN

Under an extended peacetime, the conduct of UWW within the RCN has required minimal modernization. By contrast, the same period has seen dramatic shifts in the technological landscape, and thus in the environment within which UWW is conducted. In 2017, Defence Research and Development Canada (DRDC) – Atlantic Research Centre responded to a Direct Client Support task issued by the Director Science & Technology – Navy for a system that will modernize and revolutionize the way the RCN plans and conducts UWW [1]. DRDC – Atlantic Research Centre's proposal encompasses a five-year project of research and development for a system to overhaul existing methods and procedures for predictive situational awareness, battlespace management, operational planning, and mission execution [2].

2.1 The CRACCEN project

An earlier internal publication breaks the CRACCEN project down into actionable Work Breakdown Elements (WBEs), covering the wide range of efforts required to revolutionize UWW conduct [2]. This report situates itself within WBE 1: Design Concepts for Revolutionary C2 Systems, the objectives of which are to develop design concepts and workflows for CRACCEN and to determine the best methods for visualization. Development of the CRACCEN system is expected to extend well beyond the five-year timeframe of this project, which aims only to lay the foundations for a revolutionized UWW system. For the purposes of this report, references to CRACCEN hereafter refer to the intended future system rather than the five-year project.

2.2 The CRACCEN system

The CRACCEN system is intended to support UWW command teams with automated information collation, environmental prediction, real-time modelling and simulation tools, and novel decision support tools [2]. Current planning and decision-making structures available to UWW command teams see team members operating stove-piped and individual-focused desktop software, collating data manually in order to develop situation awareness (SA), and compiling their own visual aids for course of action (COA) development and mission planning [3]. By contrast, the CRACCEN system is conceptualized to be a central collaborative environment that provides command teams with all the information relevant to their mission planning and decision-making, and that supports team discussions, collaborative COA development, and the establishment and maintenance of shared SA.

The primary focus of this report is CRACCEN's collaborative interface(s) to be used by command teams. As described in the Naval Order for Directed Client Support, CRACCEN should involve a collaborative interface capable of displaying dynamic (e.g., predictions of oceanographic conditions, environmental risk assessments, underwater threat tracks) and static (e.g., charted wrecks, marine mammal sightings, historical bathymetry) information layers to enable a central command and control environment for UWW mission planning and execution [4]. Beyond the scope of this report, the system will more broadly involve an extensive information backbone and a suite of algorithms to support the automated collection, collation, processing, analysis, sharing, and dynamic visualization of these data [2].

2.3 System requirements for CRACCEN

2.3.1 Deriving requirements

A number of semi-formal and descriptive analyses can be employed to characterize the nature of the C2 environment, with the goal of improving a C2 work system. Hierarchical Goal Analysis (HGA) identifies the goals that a work system needs to achieve in order to support its operators [5]. Because HGA focuses on goals, which may be nonlinear or parallel, rather than on the linear stream of tasks by which the goals are accomplished using current systems, it is an ideal analytical approach to deriving requirements for the design of new or revolutionary systems such as CRACCEN [6].

Past work has explored the nature of the UWW C2 environment in the RCN using HGA [3][7][8][9]. A recent report specifically identified four high-level goals for consideration in the design of CRACCEN [10]. Requirements for CRACCEN to achieve these goals are described below:

1. *Assessing Readiness*: CRACCEN should automatically collect and collate information about the status (e.g., location, bearing, weapons status, sensor status, and positioning) of own ship and task group (TG) assets, and provide that information to the UWW team, upon command, in a spatial visualization medium that is easy to parse and intuitive to interact with.
2. *Planning and Managing*: CRACCEN should facilitate both short- and long-term planning exercises by a) automatically collecting and collating data from multiple data streams to assist in building the recognized maritime picture; b) using artificial intelligence (AI) to predict future states of data streams and to produce planning recommendations; and c) providing tools to help the UWW team collaboratively build, visualize, and promulgate COAs and plans.
3. *Maintaining SA*: CRACCEN should streamline and automate the development of SA, such that UWW teams are provided a real-time overview of the area of operations (AOO) on a central display. This will decrease the likelihood that pertinent information is overlooked by minimizing the cognitive burden, and will allow teams to focus on the mission planning and execution tasks. A central CRACCEN display showing information pertinent to SA will also allow SA to be shared between members of the UWW team, thereby facilitating the collaborative development of COAs.
4. *Operational Tasks*: CRACCEN should facilitate mission execution by a) incorporating multiple sources of information (e.g., bathymetry, tactics, historical data on the behaviour of sighted enemies, intelligence) into algorithms that predict areas of high risk for enemy submarine activity; b) using AI to predict future locations of previously sighted submarines; and c) producing recommendations for sensor and asset placement in order to best protect the TG from threats.

Overlaps and interdependencies exist between these high-level goals, and together they elucidate the intended and expected use cases for CRACCEN. The focus of this report is on the display and input technologies that can support these requirements.

2.3.2 Using requirements to constrain display and input technology selection

Preliminary constraints for technology selection can be established on the basis of the requirements defined above. In order to meet the requirements of CRACCEN, at least one central display will be required; the exact nature of and methods of interacting with this central display are open to exploration. Because UWW necessarily takes place in a three-dimensional (3D) space, from the surface of the water down to the sea floor, considerations for 3D display capabilities must also be made in order to best support SA. Several methods for 3D display will be explored in this report to determine their feasibility for integration with CRACCEN. Finally, individual UWW team members are experts in their own domains and roles, and will need to complete ongoing individual work alongside the collaborative work facilitated by CRACCEN. Indeed, the collaborative work of mission planning and execution depends upon the individual expertise brought to the problem. As such, combinations of multiple displays, for a flexible blend of individual and group work, should also be considered.

Although the ability to collaborate remotely with higher command or other TG members may be a desired capability in the future, the present work focuses solely on the co-located collaborative work that will serve as CRACCEN's central purpose.

2.4 System users

Mission analyses, goal decomposition analyses, and task analyses have been conducted to identify the personnel expected to use CRACCEN, corroborated by interviews with subject matter experts (SMEs) [10][11]. Personnel expected to use the system include the Anti-Submarine Plot Officer (ASPO), Anti-Submarine Warfare Commander (ASWC), Commanding Officer (CO), Current Operations Officer (COpsO), Future Operations Officer (FOpsO), Force Track Coordinator Subsurface (FTC-SS), Operations Room Officer (ORO), Sonar Control Supervisor (SCS), and Underwater Warfare Director (UWWD). Together, these users comprise the UWW command team, though it is unlikely that all of these roles will be involved in planning and decision-making at once. CRACCEN should be able to accommodate three to five simultaneous co-located users, with the flexibility to accommodate more as needed.

3 Method

The central research question of this report can be summarized as "which display and input technologies are best suited to the anticipated use cases of a revolutionary decision aid for UWW command teams?" Even in this most simplified form the question cuts across several disciplines, as it must consider display and input technologies, characteristics of the tasks to be completed, and environmental and other pragmatic constraints. Some of these disciplines include C2, engineering, ergonomics, human-computer interaction, human factors, team cognition, and psychology. As such, the methodological approach to this report follows that of an integrative review, which aims to generate new frameworks and perspectives on a topic by reviewing and synthesizing existing literature [12]. This approach to literature review is particularly useful when a research question is too broad or interdisciplinary for a fully systematic review.

The research question (i.e., which display and input technologies are best suited to the anticipated use cases of a revolutionary decision aid for UWW command teams?) can be broken down into three distinct parts necessitating different approaches to literature search and review: (1) a description of potential technologies; (2) the suitability of the technologies for teamwork and collaboration; and (3) the suitability of the technologies for the shipboard environmental conditions under which UWW teams will be completing their tasks. Section 5 synthesizes results from all three aspects of the review and may be read alongside the summary table of the results provided in Annex A.

3.1 Databases

Databases consulted for the integrative review were: Institute of Electrical and Electronics Engineers (IEEE) Xplore, Inspec, ScienceDirect, Canadian Defence Information Database (CANDID), Defense Technical Information Center (DTIC), and Google Scholar.

3.2 Search parameters

For all literature searches described below, results were limited to those written in English and those published between 2010 and 2022, in order to ensure relevance of the findings to current and future requirements. Results which were not from peer-reviewed journal articles, book chapters, conference proceedings, or military reports were discarded from consideration. In line with published literature on best practices, searches of the Google Scholar database were limited to only the first 100 results, sorted by relevance [13]. Searches of the DTIC technical report database were likewise limited because this database is powered by Google and does not show more than the first 100 results, sorted by relevance, even when the search returns more than 100 results. For all other databases, no such limitations were applied.

For all searches, keywords of interest had to be included in the Abstract or Document Title[1]. Titles and abstracts of all results were read, assessed for relevance, and discarded if deemed irrelevant; for example, results yielded in the searches regarding the suitability of a technology for teamwork were discarded if they did not, in fact, pertain to team activities. Retained items were read fully and further screened for relevance. In the course of reading, reference lists were scanned for additional relevant references that had not been identified by the database search. These secondary sources were flagged and assessed in a similar manner; year of publication was not considered for these secondary sources, as they often provided background information or more foundational evidence.

[1] With the exception of DTIC and Google Scholar, for which Abstracts could not be individually specified as search parameters; instead, the full text was searched for these databases.

In some instances, an article uncovered in a database search revealed a conference proceeding for a specialized topic of direct relevance to the research question (e.g., IEEE International Workshop on Horizontal Interactive Human-Computer Systems). In these instances, the conference proceedings were hand-searched for additional relevant results.

3.3 Review topics

3.3.1 Review of display and input technologies

For this aspect of the review, the field of potential technologies was derived from the system requirements discussed in Section 2. Namely, CRACCEN will require at least one central display and the possibility of augmenting the display(s) into three dimensions. The results of the review of technologies can be found in Section 4.

Descriptions of display technologies were developed from existing review papers, which served to define the space of possible technologies. No review paper was consulted to describe two-dimensional (2D) displays, as the technology is well-established and most meaningful differences emerge in later considerations of input methods and task demands. Two review papers provided the foundation a review of 3D display technologies [14][15]. Additional review papers were consulted for the discussion of extended reality, which includes augmented reality (AR) and virtual reality (VR) head-mounted displays (HMDs), as well as AR with handheld devices [16][17].

3.3.2 Suitability of display and input technologies for teamwork

For this aspect of the review, searches were made for individual technologies or categories of technologies with regard to teamwork specifically, using the keywords “teamwork,” “team,” “collaboration,” and “group work.” Additional keywords selected for each technology are listed in Table 1. The results of this portion of the review are collected for discussion in Section 5.1.

Table 1: *A list of search terms used to review the suitability of display and input technologies for teamwork.*

Topic	Keywords
Display size	display size, screen size, large display
Display orientation	tabletop, horizontal display, horizontal screen, vertical display, vertical screen, display orientation, screen orientation
Mouse input	mouse input, computer mouse, multiple mouse
Pen input	stylus, styli, pen input, multiple pen, pen touch
Touch input	touchscreen, touch screen, touch input, multitouch
Trackball input	trackball[2]
Text input	text input, keyboard, speech recognition, handwriting[3]
3D displays	3d glasses, eyeglasses, 3d display, parallax display
Extended reality	virtual reality, augmented reality, extended reality, co-located, co-location

The scope of this review focused on co-located collaboration of real humans, and results pertaining to remote collaboration and human-robot collaboration were thus discarded. A large proportion of the search results for

[2] No relevant results were returned for the team-related search with this keyword.
[3] No relevant results were returned for the team-related search with this keyword.

extended reality technologies pertained to remote and/or networked collaboration setups. The additional keywords “co-located OR co-location” were thus added to this particular search in order to exclude these findings and better focus on results of interest.

3.3.3 Suitability of display and input technologies for the UWW task environment

For this aspect of the review, searches were made for ergonomic properties of individual technologies or categories of technologies, using the keyword “ergonomics.” Additional keywords employed for each technology or category of technologies is the same as those given in Table 1. Note that for these searches, the inclusion range for publication year was broadened to 2000–2022 in order to capture more results.

These searches were supplemented with targeted searches for the topics of eye strain and cybersickness, which are known issues particularly for VR and AR HMDs. Note that for these targeted searches, the author focused on experiments comparing technologies and review studies, rather than the wide range of experimental studies testing the possible etiologies or exploring real-time detection and prediction of the phenomena. Finally, targeted searches were made for the impacts on display and input technologies of known environmental conditions of the shipboard UWW task environment: ship motion and vibration.

The keywords for these supplemental searches are given in Table 2. The results of this portion of the review are collected for discussion in Section 5.2.

Table 2*: A list of supplemental search terms used to review the suitability of display and input technologies for the UWW task environment.*

Topic	Keywords
Eye strain	eye strain, visual fatigue, virtual reality, augmented reality, hmd, head-mounted display
Cybersickness	cybersickness, simulator sickness, virtual reality, augmented reality, hmd, head-mounted display
Ship motion and vibration	ship motion, physical motion, engine vibration, motor skills, manual control, input device, text input, virtual reality, augmented reality, human factors

4 Review of display and input technologies

This review outlines display and input technologies that may be considered for CRACCEN. This section is not intended as an in-depth review of all possible display and input technologies, but rather provides a brief overview of the many technologies that at least approximately meet the system requirements previously identified, so that their suitability for CRACCEN can be more carefully explored in Section 5.

4.1 2D displays

2D displays are familiar and ubiquitous technologies, available in a wide range of sizes. For CRACCEN, the target size of a central 2D display is one large enough to accommodate multiple users, but not so large as to be impractical for installation aboard a naval vessel. The orientation of 2D displays can likewise vary, from a vertical orientation to a horizontal orientation, or tilted at an angle between vertical and horizontal.

The size and orientation of a large display have bearing on a number of design constraints, which will be considered in Section 5, including how many users can concurrently view and interact with the display, the viability of various input methods, and the display ergonomics. 2D displays in a horizontal orientation are typically referred to as tabletop displays when they are targeted toward multiple users, as they allow users to stand or sit around a table-sized horizontal display and look down at the information from above. Tabletop displays are often used to digitally recreate the experience of collaborative work around a physical tabletop. The term “tabletop display” will be used throughout this report to refer to such horizontally-oriented 2D displays.

4.2 3D displays

The UWW arena, stretching from the water’s surface to the sea floor, is three-dimensional. Therefore, there are inherent limitations on the ability of 2D displays to accurately represent the AOO. UWW teams currently conduct their operations with a variety of 2D graphical systems, but the development of CRACCEN represents an opportunity to revolutionize and simplify the workflow. Although a 3D space can be inferred from the combination and/or manipulation of 2D views, providing an intuitive 3D view may lighten the cognitive load on UWW teams and free additional mental resources for the complex mission planning and execution tasks required of them [18]. A brief overview of 3D display technologies is provided below, as collated from two recent review papers [14][15]. Whereas many 3D displays have been developed for display purposes only (i.e., no consideration for user interaction) the focus below is only on those 3D displays for which interactive mechanisms have been developed, in order to meet CRACCEN’s requirements.

Perhaps the most familiar type of 3D displays are wavelength selective stereoscopic systems, which present two slightly offset and colour-shifted images to the user. The user wears special stereoscopic glasses that filter information such that only certain wavelengths (i.e., colours) reach each eye, and the effect when the two images are combined by the brain is a 3D view [19]. Similar systems use polarizing lenses to filter out a different image to each eye, with each image presented either simultaneously [20] or in very rapid succession [21].

Auto-stereoscopic (AS) systems allow for the stereoscopic viewing of 3D scenes without any special glasses by presenting slightly different information to each eye in order to invoke the illusion of depth. These systems can be time-sequential, presenting light from two different directions (i.e., each toward one eye) in rapid alternating sequence [22]; or time-parallel, with a layer between the viewer and the display that simultaneously renders a slightly different picture to each eye. Although AS eliminates the need for specialized wearable devices, it often necessitates other highly specialized hardware (e.g., [23][24]). Other AS 3D display systems produce multiple different, slightly offset images, each of which is only visible within a limited viewing zone and thus only visible to one eye at a time [25][26][27][28]. When the user moves her head, she moves through viewing zones and thus changes the view of the 3D object. Finally, volumetric 3D displays present imagery in true 3D space by illuminating volumetric pixels suspended in midair, usually within an enclosed surface [29]. Volumetric displays require specialized hardware (i.e., the display volume), and incur a high computational cost.

4.3 Extended reality displays

Extended reality is an umbrella term that encompasses the combination of virtual and real environments, with a strong emphasis on immersion and interaction: extended reality technologies allow a user to not only view virtual 3D information, but to interact with real or virtual objects while moving through real or virtual environments[4].

Per the taxonomy of [15], virtual reality (VR) and augmented reality (AR) head-mounted 3D displays (HMDs) are two-view stereoscopic displays employing advanced stereoscopic glasses. However, they are somewhat special among such technologies in that they afford a full parallax experience, wherein the 3D view changes with both horizontal and vertical head movements. As a result, they have garnered much more attention and research effort in recent years than have non-immersive 3D displays. Each is considered individually below, alongside handheld AR and spatial AR.

4.3.1 Virtual reality HMDs

VR HMDs project a virtually rendered environment onto small optical displays mounted in front of the user's eyes for a fully immersive experience [14][16]. From within the HMD, users cannot see the external world, including their own bodies and hands, unless objects in the external world are tracked and reproduced inside the virtual world. Users are therefore often given camera-tracked handheld remotes in order to interact with the virtual world. VR HMDs typically present auditory information to users through speakers positioned directly on the HMD.

Some commonly used commercial VR HMD systems today are the HTC Vive (HTC) and the Oculus Rift (Meta Technologies, LLC). Both systems currently require the HMD, and by extension the user's head, to be physically tethered to a powerful computer and it is recommended that only one headset be tethered per computer in order to ensure low latency of the displayed virtual environment. Both systems also employ handheld controllers to allow users to navigate the virtual environment and interact with virtual objects. Some VR systems employ headset-mounted cameras whereas others require a set of external cameras in order to track headset and controller motion. External cameras must be carefully calibrated every time they are moved, so it is generally recommended that they remain in one place after calibration. Other consumer-level VR HMD systems have been developed to function without the use of peripheral cameras or tethering (e.g., Oculus Go, Oculus Quest, Lenovo Mirage).

4.3.2 Augmented reality HMDs

AR HMDs are devices that overlay virtually rendered elements onto the user's view of the real world [14][16]. Forward-facing cameras track the 3D structure of the real-world environment and user-facing sensors track head and/or eye movements, allowing users to view 3D objects from all angles by moving around in physical space. Forward-facing cameras can also be used to track the user's hand movements, thereby allowing them to manipulate virtual objects. Like VR HMDs, AR HMDs typically present auditory information directly to users through speakers positioned near the ears on the HMD.

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[4] Although they are considered a form of extended reality, Cave Automatic Virtual Environments (CAVEs) immerse the user by projecting an interactive environment onto three to six walls of a room. These solutions are not viable within a shipboard setting, and are thus not considered in this report.

Like VR HMDs, AR HMDs can involve a full video screen in front of the user's eyes, whereupon a video feed of the real world is presented and overlaid with the virtual objects. More commonly, however, AR HMD screens are transparent, allowing a direct view of the real world that is then overlaid with virtual objects within a certain visual range. The Microsoft Hololens2 is presently the most commonly used example of a see-through AR HMD.

4.3.3 AR with handheld devices

Instead of wearing a HMD, users can experience video-feed AR by holding up handheld devices (e.g., smartphones, tablets) as windows onto the virtually augmented environment [16][17]. Forward-facing cameras in the devices sense the real 3D environment and present a live video feed onto the handheld display alongside virtually rendered objects. Accelerometer and gyrometer data from the device help the system track movement and accurately render the 3D objects as the user (or device) moves around in physical space, and the device's touchscreen allows users to interact with virtual objects displayed upon it.

4.3.4 Spatial AR

Spatial AR, also known as tangible AR, uses a system of cameras and projectors to track physical objects in the environment and project virtual information onto them. This allows users to view and interact tangibly with physical objects that are digitally augmented with additional visual information, without the need for glasses, HMDs, or specialized displays [17][30]. The technique can be used to display complementary text annotations on a physical object, to demonstrate texture on an un-textured object, to provide users with a virtual view into the 3D interior of an object, or to transform a non-digital object (e.g., a piece of paper) into a digital display. Common spatial AR systems employ a tabletop sandbox, within which users can shift sand to deform the physical landscape and onto which environmental details can be optically projected[5].

Spatial AR is particularly useful for architectural and design fields (e.g., being able to physically interact with a quick digital mock-up of new products), as well as for some training purposes (e.g., being able to visualize 3D organs projected onto a physical dummy for surgical training). However, its usefulness to the UWW battlespace is debatable, because the desired target for interaction is the entire surface and subsurface of the AOO. Although projecting the UWW battlespace onto a large physical 3D box could aid with general SA, user interactions would be limited by the external dimensions of the physical box. The degrees of freedom for manipulation would be insufficient to support exploration of and interaction with that 3D space for mission planning and execution. Spatial AR is thus not considered any further in this report.

[5] Physical sand tables are increasingly being superseded by virtual sandboxes facilitated by AR or VR, especially in the military domain [31].

5 Review of technology suitability

As described in Section 2, the requirements for CRACCEN recommend at least one central 2D team display for planning and decision-making purposes, a method for incorporating interactive 3D information, and the possibility of incorporating multiple displays. The primary consideration in this report is the suitability of display and input technologies for teamwork and collaboration. A secondary consideration is the suitability of each technology to the special constraints of the shipboard UWW task environment. The suitability of technologies for individual work is considered as a baseline throughout, particularly as it pertains to the selection of input methodologies and ergonomics, which have not often been studied in collaborative settings. A table summarizing the findings is presented in Annex A, which facilitates direct comparisons between technologies.

5.1 Suitability of display and input technologies for teamwork

5.1.1 2D central display

The number of simultaneous CRACCEN users may provide an important constraint on the appropriate 2D central display technologies. Results from earlier task, mission, and work analyses suggest that CRACCEN should be able to accommodate a group of three to five co-located SMEs, with room for further users as needed [10][11]. Because multiple users are anticipated to interact with CRACCEN simultaneously, larger displays (i.e., greater than 32") should be considered as the central display technology for CRACCEN. A recent review of large displays found distinct advantages over more traditional individual displays (e.g., desktops, laptops) in facilitating communication, coordination, and workspace awareness [32]. Research comparing "small" (17") and "large" (33") displays directly has shown that larger displays more readily support an equitable distribution of collaborative task activities than do smaller displays [33] (c.f. [34], which found increases in the quantity of communication with smaller central displays, likely as a compensation for the smaller and less effective information display). Handheld 2D display devices on their own are not ideal for collaborative work, as they discourage communication, decrease workload equity, and lower the quality of solutions, relative to larger shared workspaces [35]. Space constraints aboard a naval vessel generally provide a practical upper limit on the size of a central 2D display, though previous work has shown full-wall (e.g., 120") displays can improve shared SA in military command teams at land-based command centres [36][37].

Screen display orientations include vertical, horizontal (e.g., tabletop), or angled displays that fall between vertical and tabletop orientations. Tasks that will require users to spend a large portion of their time interacting with the system may benefit more from vertical displays, whereas tasks requiring a lot of interpersonal interaction, including group situational understanding, discussion, and non-parallel work, may benefit more from tabletop displays [38]. Indeed, tabletop displays are typically reported to naturally and comfortably support efficient collaboration and face-to-face communication, by leveraging the familiar schemas of collaborating around a physical table and incorporating naturalistic communication modes to facilitate knowledge transfer [33][39][40][41][42][43][44]. The ability to work around any edge of the screen also allows for partitioning of individual work spaces that can later be combined for group-level activities [45][46]. Feedback notifications about other users' actions may reduce work redundancies and increase SA during such parallel tasks [47]. By contrast, communication around a vertical screen is less natural and more asymmetrical (e.g., one person talking, others listening), and is typically associated with decreased role switching, idea exploration, and other-awareness [39] (c.f. [48]).

Whereas vertical displays are better suited to shorter and more focused tasks with fewer users, because the vertical orientation limits users' ability to interact with the screen without bumping into one another, tabletop displays are better suited to tasks of longer duration that require more discussion [33]. Some research suggests that a full-wall display shared between few collaborators does not carry the same limitations on collaborative work as smaller vertical displays [49], likely due to the increased surface area and space for communication. Less research has examined tilted screens that fall between vertical and tabletop orientations. Although initial evidence suggests a tilted screen may be preferred over vertical and tabletop screens for pairs of collaborating users [50], it is not clear whether the preference predicts better performance, nor whether the preference would hold for collaborations between more than two users.

Despite the apparent benefits of tabletop screens for collaborative work, it must be noted that distributing users around all edges of a tabletop screen introduces complications with the orientation of displayed elements [51][52]. Considerations for orientation would need to be made during user interface design for a tabletop display in order to ensure that multiple users can effectively comprehend, communicate about, and coordinate on the information presented [53]. The orientation of text information presents a particular challenge for tabletop displays, because the orientation of text relative to a reader has a significant impact on reading speed and accuracy. However, solutions exist for rotating and translating digital objects on horizontal touch displays, whether manually or automatically via sensors that detect users [54][55]. User orientation around a tabletop display is less of a concern when the primary information to be presented is spatial or graphical rather than textual. Notably, however, research suggests that groups tend to cluster around one edge of a tabletop display in order to share a common perspective of a 2D map [56], because users find spatial navigation disorienting when they view a map from different angles [57].

Flexibility may be built into the CRACCEN system by allowing the central 2D display to be convertible between vertical and tabletop orientations, to accommodate different task requirements [58].

5.1.1.1 Input methods for 2D displays

Input methods refer to the technologies and mechanisms that allow users to interact with information presented on a display. Input methods can involve direct mapping between the user's actions and the display (e.g., direct touch screens, pen styli[6]) or indirect mappings, whereby the user's movements are captured by some device that translates to movement on the display (e.g., mouse, trackball).

Comparing direct and indirect input methods for individual users, direct touch input is faster, more accurate, and preferred relative to mouse input when the task is bimanual. By contrast, all metrics generally favour the mouse in most studies of single point interactions (e.g., [59][60]), except when the task involves drawing or games [61]. [62] found increased speed but decreased accuracy for single touch inputs relative to mouse and stylus inputs. For tasks requiring a high degree of precision, mouse input is generally preferred to touch input [59][62][63], except when manipulation of 3D information is required [64]. When high precision is not required for a task, mouse input is slower than direct touch input [65].

The familiarity of mouse input is likely a contributing factor in many of the comparisons above, as touch input accuracy appears to improve with experience [66]. Indeed, more recent studies indicate little difference between touch and mouse input for some tasks, perhaps reflecting the public's growing familiarity with touchscreen technologies since the commercial proliferation of handheld touch devices [67]. A variety of software-based adjustments to direct touch input show promise for overcoming its inaccuracies for small targets [68]. Pen styli can also offer improved precision because their point of contact is smaller and produces less occlusion and incidental touches than a finger [62][69][70], but the trade-off may be reduced speed compared to finger touch [71]. The incorporation of visual feedback when hovering a tracked pen stylus over a surface (e.g., comparable to a mouse cursor) can offer slight improvements to speed and dramatic improvements to accuracy of stylus inputs [72].

Trackball movement is both slower and less accurate than traditional mouse movements for most tasks, due to the difficulty of translating the rotary movement of a trackball to the linear space of a 2D display [73]. On larger

[6] A pen stylus is a pen-shaped tool used for input on touch devices. It provides users with a fine tip for higher precision inputs than can generally be achieved with a finger.

displays, keeping track of a cursor for indirect input mappings can prove challenging, particularly when mouse or trackball acceleration is set to high [74]. When input device acceleration is set to low, it can become tedious to move a cursor across a large display. There is some evidence that trackballs have an advantage when moving across a large display at a high velocity, but users still suffer from decreases in speed and accuracy when slowing down to select a target [75].

Direct touch input carries its own drawbacks for larger displays. For example, users find dragging and object rotation tasks more difficult as the display size increases [76]. A user's ability to interact with information on the screen is also necessarily limited by the extent of her reach, which is in turn limited by the display orientation and whether she is seated or standing [77]. External tracking cameras can be employed with gesture-based inputs to extend reach on large displays [78], or to identify and differentiate individual user inputs [79]. Pen styli can also be used to differentiate simultaneous inputs from multiple users.

Finally, the relative nature of mouse and trackball inputs become less intuitive on tabletop displays, where users can be situated on any edge of the screen such that the relative motion of the cursor may not correspond to the direction the mouse or trackball is moved from the user's perspective. Critically for the purposes of CRACCEN's multi-user setting, it is difficult for users to locate one another's cursors and track movements when multiple indirect inputs are used [38][80][81][82].

Multiple mice may also decrease other-awareness and collaboration in favour of divide-and-conquer strategies, compared to single-mouse setups [83] (c.f. [84], which shows a potential role for multiple mice in mixed-focus collaborative tasks on wall-sized displays). By contrast, direct touch input improves other-awareness in collaborative tasks, because of the ease with which others' interactions with the display can be seen [82][85][86][87]. Likewise, both verbal and non-verbal communication improve when teams use individual tablet computers compared to individual small netbook laptops with keyboards [88], suggesting that the benefit of direct touch input for teamwork may hold true regardless of screen size. Indeed, direct touch and pen inputs provide better supports for interpersonal interaction around collaborative displays than do indirect (e.g., mouse) inputs, because they allow for gesturing, more effortless awareness of other users' actions, and more naturalistic inferences about intentions [80][81] (c.f. [89], which showed no difference in collaborative task performance or individual preferences between mouse and touch inputs to a tabletop display). Direct multi-touch around a tabletop is particularly conducive to communication and equitable collaboration, compared to single touch, single mouse, and multiple mouse inputs [90]. Currently available touchscreens support a high level of multi-touch (e.g., upwards of 30 simultaneous touch inputs), allowing multiple users to interact intuitively and simultaneously with a display, with or without the aid of pen styli.

5.1.1.2 Text input for 2D displays

Although the various task analyses that have been conducted on command team members suggest that CRACCEN usage will not involve a substantial amount of text input [10], it may nevertheless be necessary for users to enter data, annotate information, or type short notes to one another.

Generally speaking, physical keyboards provide the most familiar method of text entry, and thus produce the fastest and most accurate results without training. However, multi-user interactions with the display would require either multiple physical keyboards, which take up space and clutter the workstation, or a single keyboard that can be used in turn. For vertically oriented displays, the placement of a physical keyboard is self-evident, as it makes ergonomic sense to have keyboards placed in front of vertical displays. For tabletop displays, however, the appropriate placement of physical keyboards is not immediately apparent, since users can interact with a tabletop display around any edge.

An alternative to physical keyboards is digital touch or soft keyboards, which can be used with any touch display. Unlike physical keyboards, soft keyboards can be rotated, moved, and resized to accommodate user needs around a vertical or tabletop display, and multiple soft keyboards can be available for simultaneous text entry tasks. Soft keyboards may thus be better suited than physical keyboards to collaborative work on large displays, although methods to improve speed and accuracy should be considered during the design phase. Usability studies, for example, have found that soft keyboards yield lower speed and accuracy than physical keyboards, likely due to the absence of haptic feedback from physical keys [91][92]. Dynamic resizing of keys based on letter-prediction algorithms has shown some promise in increasing speed and accuracy [93], as has adaptive re-spacing of keys in response to personal ergonomic habits [94][95]. Care should be taken to minimize input latency and, where possible, introduce other modalities of keystroke feedback (e.g., sound, vibration) in order to improve performance and usability [96][97].

Soft keyboards can also be activated by pen stylus touch, although this limits input speed greatly relative to the use of all ten fingers. A gesture-based solution allows for users to type without lifting a finger or stylus as they move through visually presented letters [98]. However, because these keyboards present characters in layouts designed to increase gesture fluidity (i.e., circular layouts), they are unfamiliar and therefore difficult to use [99].

Natural handwriting on touch surfaces with either pen styli or fingers allows for an intuitive text entry method and handwriting recognition algorithms are now sufficiently advanced to provide fast and accurate input processing. Notably, speed and accuracy of handwriting are much higher with pen styli with than fingertips [100]. However, the speed of this method is limited to the speed of human handwriting, rendering it significantly slower than other text entry methods [91][99]. Handwritten text entry may thus be suitable for brief annotations, but less suitable for longer entries.

Speech recognition software, which employs natural language processing to listen for and interpret speech, is another intuitive method of text entry that may have benefits over typing for short messages [91][101]. However, the viability of the method for CRACCEN is less promising, as the software would need to be able to recognize and distinguish between multiple users in an environment with high ambient noise and highly domain-specific terms and acronyms. One major hurdle for speech recognition software in a collaborative environment is the need for the system to differentiate between verbal inputs intended for the system and ongoing communication between teammates [102].

5.1.2 Incorporating 3D information

Because UWW takes place in 3D space, CRACCEN should incorporate some ability to visualize and interact with the AOO in 3D. Section 4 outlined several potential approaches to 3D augmentation. The suitability of 3D displays are discussed briefly below, before turning specifically to VR and AR displays, for which much more research on applications to teamwork exists.

5.1.2.1 Stereoscopic and auto-stereoscopic 3D displays

Overall, little work has directly examined the use of stereoscopic and auto-stereoscopic 3D displays by multiple simultaneous users. However, a few conclusions can be inferred from the user experience of such displays for individual users.

Interaction with 3D displays viewed through stereoscopic glasses faces complications from the illusory nature of the 3D image: whereas the image appears in 3D, the surface upon which users can interact with the image remains two-dimensional. This has implications for the accuracy of touch input [103], since a user cannot simultaneously converge her eyes on her finger/stylus at the surface of the screen and on the 3D image of the object, which appears either in front of or behind the screen [104]. The result is that either her finger/stylus or the 3D image will appear blurred and doubled. To resolve this issue, mid-air 3D touch can be supported with cameras that track hand/stylus movement [105][106][107][108][109]. However, the image seen through stereoscopic glasses is distorted and can cause user discomfort when viewed at different vertical or horizontal angles than front and centre [110]. This limitation calls into question the viability of stereoscopic glasses for multiple users interacting around a display, and particularly at the angle required for a tabletop display.

Other technologies such as the Euclideon Holographic Table (Euclideon Pty Ltd) allow multiple users wearing special stereoscopic glasses to view and interact with detailed 3D objects in ways that mimic holography (see also [111][112]). A 3D image appears as projecting from a tabletop surface and cameras track users' glasses in order to display the correct viewing angle as they move around the table. Multiple users are able to see different angles at the same time because the computer projects appropriate viewing angles for all users onto the table at individual ranges of light frequencies. The user's glasses filter the light so that only the frequency range appropriate to their viewing angle is seen. Tracked styluses moreover allow multiple users to interact with the 3D images.

Auto-stereoscopic (AS) systems are limited in the number of "sweet spots" from which the 3D object can be accurately viewed [15]; user numbers are thus limited and viewing angle is restricted. More recent innovations have incorporated eye or head tracking to adjust the display such that the "sweet spot" moves with the user [113], and further innovations in multiple-user tracking have allowed for simultaneous AS 3D views [114][115]. In all cases, these technologies work best when the surface of the screen is approximately parallel to the user's face, and thus place limitations on display orientation and the distribution of multiple users. Because they rely on 2D display surfaces, AS systems generally carry the same restrictions on user interaction as do stereoscopic glasses, although some promise has been shown with motion-tracked mid-air gesture inputs [115]. By contrast, volumetric displays, in which pixels are suspended in midair within an enclosed 3D surface, do not carry the same restrictions on interaction. Users can interact with the 3D images in a limited capacity by touching the external surface of the enclosure [29], and more recent innovations allow a higher level of interactivity with motion-tracked gesture inputs [30] or angle- and pressure-sensitive stylus input [116].

5.1.2.2 Extended reality displays

VR HMDs have shown some promise in augmenting SA in collaborative planning tasks, as a complement to traditional planning over 2D maps [117]. Indeed, VR HMD systems are regularly proposed for remote collaboration, as they allow for a shared awareness of virtual environments and facilitate otherwise difficult interactions over a distance (e.g., [118][119]). However, such systems impose limitations on the capacity for co-located collaboration, because the external world, including one's collaborators, is occluded and replaced by a full-view virtual display. Compared to face-to-face collaborative work in a real environment, collaborative work using VR HMDs suffers from an increase in miscommunications and collisions [120]. This is due to an inability to see the actions, gazes, movements, and non-verbal cues of collaborators. The result is a decrease in performance on some collaborative tasks compared to see-through AR HMDs [120]. The effects can be somewhat mitigated by tracking the movement of users' bodies and incorporating a digital avatar for each user into the virtual world [121][122]. But important cues such as gaze direction are not easily read from such avatars and they may not aid task performance [123]. Other approaches to these limitations render a user's pointing (e.g., by finger or input device) as a visible ray in the shared virtual environment, or employ algorithms to combine different users' views for a more complete view of the collaborative virtual environment [124].

VR HMDs may be more appropriate when the majority of the work to be completed is loosely coupled individual work, interspersed with short periods of discussion and tightly coupled collaboration [125]. Some research has proposed combining a single VR HMD with a secondary view of the virtual scene on a handheld AR device, which yields similar communication and performance results as a setup with two VR HMDs [126] (see also [127][128][129]). Research on such asymmetric use of VR HMDs is still in its early stages and may soon provide guidelines on asymmetric setups for different styles of collaborative work [130][131][132].

See-through AR HMDs such as the Microsoft HoloLens2, by contrast, allow for multiple users to safely interact in the same space. Co-located collaborative use of AR HMDs has been demonstrated with upwards of eight simultaneous users [133]. The literature in fact recommends see-through AR HMDs for successful and safe communication between co-located collaborative users [120][134][7]. Multiple-AR-HMD setups support each:

[7] It has been suggested that AR HMDs may nevertheless restrict the expression and perception of nonverbal cues by obstruction of the eyebrows and gaze information [135]; more research on the actual impacts of such obstruction is needed.

1) tightly coupled interactions, wherein each user can manipulate the same 3D scene (e.g., [31][134]); 2) driver-follower interactions in which one user actively controls the scene and other users simply view the changes being made (e.g., [136]); and 3) loosely-coupled interactions, wherein each user manipulates their own independent view (e.g., [137]). This ability to switch between multiple levels of interactivity provides important flexibility for collaborative work. As with VR HMDs, collaboration and communication with AR HMDs can be facilitated by rendering a user's point or gaze as a visible ray in the shared virtual environment [138].

Compared to VR HMDs, users completing tasks using AR HMDs maintain greater awareness of the real world and at levels comparable to completing the same tasks without any HMD [139]. AR HMD systems reduce the separation between task space and communication space, and facilitate natural communication cues to improve both task performance and communication metrics [140][141]. Moreover, the see-through nature of AR HMDS allow for continued interactions and collaboration between users even when some are not wearing HMDs [142]. Such asymmetrical use of AR HMDs in teams may in fact improve communication quality, relative to teams with no AR HMDs [143]. Research has demonstrated an advantage of AR systems, over and above traditional methods of SA and planning, in co-located teams of firefighters, police, and military planning personnel [144]. This use case has obvious parallels with the intended application of CRACCEN. Likewise, the U.S. Navy and Army have recently demonstrated AR HMDs as a useful tool for collaborative command and control tasks [145][146].

AR HMDs may be particularly appropriate in combination with a tabletop display, such that users can move fully around the tabletop to view a 3D scene from every angle without losing sight of the tabletop or their collaborators in the real world (e.g., [147]). This setup would also resolve complications with text orientation on tabletop displays, because AR HMDs can render text in an orientation appropriate to each user. This combination benefits from the rich depth cues provided by AR to visualize information, and the ease and familiarity of touch input on a tabletop display [137]. It has proven a useful combination for urban visualization [148][149], architectural design [150], and aerial mission monitoring [134], all of which involve visualization of 3D objects (i.e., buildings, airplanes) and 3D space extending from the horizontal surface of the ground. UWW could similarly benefit from combining AR HMDs and tabletop displays, as SA in this realm involves visualization of 3D objects (i.e., ships and submarines) and 3D space extending from the surface of the ocean floor.

Handheld AR offers an alternative to HMDs, although interactions with 3D objects via tablets have been shown to be slower, more physically tiring, and less preferable compared to AR HMDs [151]. An examination of handheld AR for a collaborative navigation task found significant advantages of handheld AR maps over traditional 2D virtual maps in facilitating communication, establishing a common understanding, and encouraging discussion [152]. Likewise, allowing for individually manipulable views of a 3D object can aid in teaching and learning [153]. However, handheld AR for group work may be associated with a higher workload, particularly for complex problems, which can in turn hinder communication and collaboration [154]. Indeed, whereas VR HMDs are less effective than fully see-through (e.g., AR) HMDs at promoting effective communication between collaborators [120], both task and communication performance suffer with handheld (e.g., video feed) AR compared to VR HMDs [126]. For a full review of mixed and augmented reality in collaborative task settings, see [155][156].

5.1.2.3 Input methods for 3D displays and extended reality

When 3D information is presented on 2D displays, several familiar input methods exist. Direct touch (e.g., on handheld AR devices) and indirect mouse dragging can be used to pan, tilt, and rotate in 3D space, whereas gaming controllers often use dual joysticks to facilitate 3D navigation. Within design industries, the 3D mouse is a common solution for the manipulation of 3D objects on 2D displays, providing six degrees of freedom for movement along all axes (e.g., SpaceMouse by 3DConnexion, Logitech). Gesture-based methods have also been developed for direct touch manipulation of 3D objects on 2D displays [157],

Such input methods are less feasible for interaction with VR and AR HMDs [158]. More commonly, HMDs use either motion-based hand tracking to support virtual "direct" touch in mid-air, or infrared-sensor based tracking of handheld remotes for the indirect selection and manipulation of virtual objects. Both input methods allow the user to interact with virtual objects in a way that reinforces immersion in the 3D environment.

Most off-the-shelf VR HMDs come equipped with infrared-tracked handheld remotes. Users aim a laser cursor projected from the remote toward a virtual object and can press one of several buttons to perform different interactions. VR HMD systems can also track hand motions for remote-free gesture inputs, and offer comparable performance and usability to handheld remotes [159].

Because of the nature of AR environments, gestures and mid-air "direct" touch are the most common forms of input with AR HMDs. Research has shown that bimanual manipulation of 3D scenes aids users' understanding of the 3D space by providing the user's own body as a natural spatial referent [160]. Although intuitive and natural to perform, pre-defined gestures may not match the user's assumed and preferred function, and may thus be difficult to learn and remember [161][162]. User-defined gestures may circumvent some of these complications [162][163]. The Microsoft HoloLens2 supports accurate onboard recognition of simple hand gestures by the outward facing tracking cameras for input. Other devices, such as the Microsoft Kinect, can be tethered to an AR or VR HMD system in order to expand the range of available gestural inputs and allow for custom user-defined gestures [163].

Tracked remotes are less common with off-the-shelf AR HMDs, but may provide some usability and ergonomic advantages compared to mid-air "direct" touch [164]. Unlike tracked handheld remotes, mid-air "direct" touch suffers from an absence of haptic feedback, which can impair accuracy, speed, and perceived ease of use [164]. More recent work has examined the use of tethered smartphones [165] or tablets [166] as tangible input devices for collaborative work in AR environments. Other forms of feedback, such as auditory cues, could be incorporated to support mid-air manipulation of virtual objects displayed on AR HMDs, but consideration must be made for ambient noise within the shipboard operational environment [167].

Because the particulars of a given 3D input method are tied so closely to the display technology (e.g., proprietary remotes for VR HMDs and built-in gestures for AR HMDs), and because literature searches yielded no results pertaining to suitability of 3D input methods for teamwork and collaboration, the results from this section are not independently considered in the summary table in Annex A.

5.1.3 Combining multiple displays

Although CRACCEN's requirements suggest the need for at least one central 2D display, the system need not be limited to a single display technology. Indeed, there may be some benefit to incorporating multiple technologies for complex tasks involving multiple users [168][169]. Research examining collaborative group work considers the concept of coupling, a measure of how involved with one another's work collaborators are (e.g., [170]). For tightly coupled tasks, group members work in close collaboration toward one or several common goals, making decisions and implementing changes by deliberation and consensus at the level of the group. For loosely coupled tasks, group members may work in parallel on different aspects of a problem in order to collectively reach a goal; decisions are made at the individual level or occasionally in looser consultation with other group members. Mixed-focus collaborative tasks involve a mixture of both loose and tight coupling, and involve transitions between the two according to the flow of task requirements [56][84][168]. The workload level of a given task may influence coupling and information-sharing requirements as well. For example, team performance under a high workload may suffer when coupling is either too loose (e.g., no information is being shared between team members) or too tight (e.g., all information is being shared between team members), whereas a low workload condition may benefit from looser coupling [171].

The sorts of complex mission planning and execution tasks to be completed by the UWW team using CRACCEN are expected to involve mixed focus and a variety of workload conditions. Because the balance of loose and tight coupling in mixed-focus work might be expected to vary across individual UWW command teams [40], and across tasks and workload conditions, flexibility of the selected technologies may be of general benefit. Combining multiple displays for CRACCEN could facilitate this flexible coupling.

In one possible configuration, handheld devices for individual work could be provided, which can later send data to the central group display for discussion and further collaborative work [34][35][172][173][174][175][176]. Similarly, tethered handheld devices have been demonstrated as alternate input methods to large group displays [175][176][177]. Interestingly, the aforementioned differences between vertical and tabletop orientations in promoting collaboration and communication (e.g., [39]) may be diminished by the introduction of auxiliary handheld devices, which allow work to be more distributed [178]. Docking stands that hold handheld devices at a comfortable height and angle (e.g., [179]) can be placed around the group display to facilitate the aggregation and discussion of individual work. Desktop computers may also be incorporated in a mixed focus collaborative system, and the combination of multiple displays for different aspects of group work has shown promise in complex decision-making tasks [172].

One of the major hurdles for mixed-focus system design is the balance of awareness: ensuring that collaborators remain aware of one another's actions and the group-level state of progress on a task, while also being able to maintain focus on their own individual work [170][180]. Some research has found decreased levels of collaboration when handheld devices were incorporated with tabletops [181]. This deleterious effect may be alleviated by notifications and alerts that help maintain other-awareness [47], while information linkages between devices can help users switch fluidly between devices and task modes [182][183][184][185].

Design for multiple integrating technologies must also consider the more practical challenges of system complexity and technological troubleshooting. Auxiliary devices networked to a central group display and/or to one another may introduce frustration and barriers to use in the form of poor integration, mismatching software updates, bandwidth limitations, network connectivity, device communication issues, and higher maintenance requirements for multiple devices and their integration. The trade-off between system flexibility and complexity must be further examined.

5.2 Suitability of display and input technologies for the UWW task environment

The UWW task environment is necessarily constrained by the physical shipboard environment within which UWW command teams will use CRACCEN. Environmental considerations such as ambient noise, physical space, temperature, humidity, and lighting will certainly play a role in how CRACCEN is developed and used. However, CRACCEN is a future technology being developed for future ships, and therefore is not constrained by the physical environment aboard existing ships. This section focuses only on those conditions of the UWW task environment that cannot be resolved by future ship design choices, and which will be useful in differentiating between the different display and input technologies under consideration.

5.2.1 Eye strain from display technologies

Though any electronic display can cause eye strain and visual fatigue, especially after prolonged use, evidence suggests that the likelihood and severity of symptoms is greater for AR and VR HMDs than for common 2D displays [186][187][188] (c.f. [189]). Stereoscopic viewing, including via HMDs and stereoscopic glasses systems, may exacerbate eye strain due to a mismatch between vergence (adjusting the rotation of the eyes to converge to an object's distance) and accommodation (adjusting the focus of the eyes to the distance of an object) when viewing virtual 3D objects [190][191][192][193][194].

Although some research suggests that see-through AR HMDs promote better depth estimation, greater interaction precision, and less eye strain than VR HMDS [195][196], the likelihood of eye strain symptoms should be a serious consideration for both AR and VR HMDs. Designers must be aware of best practices to minimize eye strain and improve user experience and wellbeing [197][198]. Common AR and VR HMDs have a set focal distance at either infinity (HTC Vive) or approximately 2 metres (Oculus Rift, Microsoft HoloLens2). Infinite focal distances simplify the mathematics for developers but increase the likelihood of eye strain [199].

Virtual objects that users will need to focus on should be projected at a perceived distance of no less than 0.5 m from users' eyes [200]. Tasks requiring users to switch between more near and more distant interfaces should be avoided, as moving the focus along the z-axis can aggravate vergence-accommodation conflict and strain [199][200][201]. Notably, see-through AR HMD systems may require users to switch focus between the virtual objects projected near the eye and more distant real-world objects. It is recommended that virtual objects in such systems are projected at a perceived distance between 1.2 metres and 5 metres away from the user for optimal comfort and resistance to eye strain [200][202].

Various adaptive algorithms have been developed that may minimize the occurrence of eye strain and visual fatigue from HMD usage by dynamically adjusting the user's view [203][204]. The use of "dark mode" graphics, where light text and graphics are positioned against a dark background, may alleviate eye strain symptoms in VR HMDS [205]. Likewise, employing light-coloured graphics in a dimly lit environment will result in optimal user experience and comfort with AR HMDs [206]. There is also some evidence that training and experience with HMDs can improve eye strain symptoms [207][208].

5.2.2 Cybersickness from extended reality HMDs

VR users often experience a phenomenon known as cybersickness or simulator sickness, the symptoms of which include nausea, fatigue, disorientation, headaches, and general discomfort [209][210][211]. The symptoms can last for hours after removing a VR HMD and may ultimately discourage use or hinder performance on tasks in the real world [211][212][213][8]. Although not fully understood, research suggests that cybersickness is caused by sensory conflict, or mismatches between expectation and perceived reality—whether resulting from insufficient refresh rate of the projected image, latency issues, poor tracking of the user's head motion, or mismatch between the visual and vestibular systems (i.e., the user sees that they are moving quickly through a scene but the vestibular system in the ears does not register any motion) [209][212][215][216][217][218]. Eye movement training immediately prior to VR usage may mitigate the likelihood of cybersickness symptoms [219], although more research is needed to validate this effect with a larger sample size. Likewise, techniques used to condition individuals to motion sickness may alleviate the propensity to experience cybersickness over time [220].

The propensity to develop cybersickness differs between individuals and between VR applications, and much effort has been devoted to developing means of detecting and mitigating cybersickness in real time (e.g., [221][222][223][224]). Because increased length of HMD use is generally associated with increased likelihood and severity of cybersickness symptoms, designers should only consider HMDs as supplementary displays for CRACCEN (c.f. [225]). Multiple review papers have catalogued the high level of individual variability in the experience and time course of cybersickness using HMDs [226][227].

Little research has explored the possible interactions between cybersickness effects in a virtual world and real whole-body motion. Users at sea experience continuous whole-body motion, particularly on rough seas (see Section 5.2.3), which may amplify the mismatch between perception and expectation in a VR environment and thereby increase the risk of cybersickness. Such amplification effects have been observed when passengers in moving vehicles or motion platforms used VR HMDs (c.f. [228]), and efforts to incorporate synchronized visual indicators of the external motion may either alleviate [229][230] or further exacerbate [231] symptoms. Other research has failed to find an increased risk of cybersickness symptoms when AR or VR HMDs were used under conditions of simulated ship motion, compared to no motion. However, the effects of ship motion without an HMD were not assessed so the effects of cybersickness and seasickness cannot be differentiated [232]. As a further complication, some research suggests that VR HMD users may consciously or subconsciously limit their head movements when experiencing shipboard motion in order to offset the felt or anticipated effects of sickness [233]. There is also some evidence that cybersickness from VR HMDs may negatively impact balance and

[8] C.f. [214], which showed that impairments to simple and complex reaction times after VR use were only weakly correlated with symptoms of cybersickness, suggesting that VR use was itself responsible, regardless of cybersickness symptoms. This is a concerning finding worthy of further exploration.

postural stability [234][235], which may be a risk factor for accident or injury aboard a moving vessel. Undoubtedly, the interaction cybersickness and ship motion needs further study, particularly within the unique population of experienced naval personnel.

Although AR HMDs do not seem as likely as VR HMDs to induce cybersickness [195][236] (c.f. [237][238], which found no evidence of cybersickness using either VR or AR HMDs), AR HMD users can still experience sickness symptoms caused by eye movements [239]. For example, interpupillary distance varies between individuals and misalignment with the HMD's settings can frustrate stereoscopic accommodation and convergence, leading to symptoms of fatigue and headache in some users [240][241]. Some HMD systems such the HoloLens2 have built-in settings to adjust interpupillary distances for unique users, and can recognize individual users through a locally stored retinal database to automatically adjust interpupillary distance for optimal stereoscopic viewing. Nevertheless, AR HMD use provokes a higher reported incidence of cybersickness than does handheld AR, and some preliminary evidence suggests symptoms could linger after prolonged usage as they do with VR HMDs [239]. More research is needed to validate the health and safety of AR HMD use aboard naval vessels.

5.2.3 Impacts of ship motion on input technologies

Turbulent conditions, such as those induced by ship motion on rough seas, can negatively impact the accuracy of input on electronic devices [242][243], whether directly or by indirect means (e.g., via increased fatigue or seasickness [244], or impaired visual tracking [245]). Fine motor movement is particularly affected, which renders direct input (i.e., touch, pen styli) more difficult than indirect methods such as mouse, trackball, or keyboard inputs [246][247]. In studies of simulated ship motion, the accuracy of touch input is shown to dramatically worsen as ship motion increases, particularly for smaller targets and gesture-based inputs [248][249]. Mouse input, by contrast, is fairly resilient to simulated ship motion [248]. Although trackballs are often considered optimal input devices to withstand ship motion, [248] also found that trackball input was consistently slower and less accurate than mouse and touch input, even under heavy simulated ship motion (see also [250]).

In simulations of turbulent aircraft conditions, touchscreen users experience decrements to overall performance, usability, and comfort [251]. This is especially true as the display size decreases, suggesting that a large group display may not suffer from the detrimental effects of motion to the same extent as handheld devices [252]. Touch performance is improved when users can brace their hands or wrists in some way, but this can introduce new ergonomic complications from unnatural or difficult finger reaching [253][254]. It is not known to what extent the accuracy of extended reality gesture inputs would be similarly hindered by ship motion, and future research must explore this possibility. Research has, however, demonstrated significant detrimental impacts on accuracy using physical inputs (i.e., a computerized shooting task) when military members wore either AR or VR HMDs under conditions of simulated ship motion [232]; there was no difference in effect between the two types of HMD.

Of secondary consideration, the use of peripherals for indirect (e.g., mouse) or direct (e.g., pen styli) inputs introduces additional complications from ship movement. Peripherals left unfixed and unattended to could slide away from their display devices and cause damage or loss.

5.2.4 Impacts of ship vibration on display and input technologies

Whereas a ship's motion on rough seas can be considered a low-frequency vibration, the sorts of whole-body high-frequency vibrations usually referred to by the term also have an impact on the motor and cognitive abilities of ship personnel and thus must be considered in both display and input technology selection [255]. Higher frequency vibrations such as those produced by engines or other onboard machinery can affect the stability of vision and fine motor skills [256], leading to errors in both perception and input accuracy [257]. A meta-analysis found that higher-frequency whole-body vibrations could have a greater detrimental effect on performance than lower-frequency vibrations, particularly for tasks requiring a high degree of input accuracy [258], although the amplitude of the vibration may be a more critical factor than its frequency [255]. As with lower frequency ship motion, one would expect that input performance with larger displays, which afford larger targets and thus require less precision to operate, would be less affected by high-frequency vibrations than would smaller displays. Research comparing input methods found that the speed and accuracy of trackball inputs were more negatively affected by engine vibrations than mouse or touch inputs, which did not differ from one another [259].

HMDs could exacerbate the deleterious effects of vibration on vision, since both the eyes and the screen in front of them could experience vibratory jitter. The extent to which the amount of vibration experienced in the operations room would hinder comfortable usage of HMDs is a worthy topic for further study before extended reality HMDs could be incorporated into shipboard systems. Previous use of HMDs in military settings has demonstrated that problems with vibration in airborne and ground vehicles can be ameliorated with careful attention to proper mounting of the HMD to the user's head [260]. This feedback pertained to custom designed US military HMDs, however, and may not be applicable to the systems eventually procured by the RCN.

Finally, if vibratory feedback or alerts are relevant to CRACCEN's functioning, then the ability of users to perceive such feedback through the noise of whole-body vibration needs to be assessed. This is a particularly relevant concern for handheld devices but could also be a factor for soft keyboards and direct touch input on large displays, which may benefit from vibratory keystroke feedback [96][97].

5.2.5 Ergonomics of display and input technologies

The ergonomic characteristics of devices are of critical importance for long-term or frequent technology use, as they can greatly impact user morale and wellbeing. It has long been known, for example, that prolonged computer mouse usage is associated with musculoskeletal disorders such as carpal tunnel syndrome (e.g., [261]). Alternative input devices have been developed to alleviate the ergonomic strain, but users tend to prefer the traditional mouse to learning novel input methods, which often require considerable training to show any ergonomic or usability benefits [262][263][264][265]. Trackballs may provide more ergonomic support than traditional mouse input devices, provided that care is taken to reduce extreme wrist postures in the trackball's placement, with consideration for individual user ergonomics [266]. Supports to the forearm and palm may offset the ergonomic strain of standard mouse [267] and keyboard [268] inputs. Comparisons between standard computer mouse and pen stylus inputs (i.e., on a horizontal input pad) with a desktop setup show either no differences in muscular load [269] or greater muscular load from pen stylus use [270], depending on the specifics of the experimental setup. By contrast, pen stylus input on a slanted touch screen tablet, with both forearm and tablet resting on a horizontal surface, induced less wrist strain and higher user comfort than standard computer mouse input [271]. For text input, soft keyboards show an ergonomic advantage relative to physical keyboards in the short term due to decreased typing force, but a disadvantage in the form of increased shoulder strain over the long term [272].

Comparing tablets, laptops, tabletops, vertical displays, and smartphones, only the laptop was found to be suitable for long-term use, and only when a proper seated posture was encouraged [273]. The remaining devices were shown to cause significant strain on shoulders, necks, and arms. The same study showed that large vertical displays, when used from a standing position, were particularly straining and not recommended for long-term use (see also [274]).

Large touchscreen displays have been shown to cause more muscle fatigue when displayed in a vertical rather than tabletop orientation [275][276], which can compound into more lasting damage to the musculoskeletal system. Researchers recommend reducing the extent of continuous interaction required and circumventing the need for distant interactions on large displays by bringing important interfaces closer to the user [275][277]. The reach distance for comfortable touch interactions on a tabletop display, for example, is smaller than the size of many large displays [77], so designers need to consider the layout of interfaces carefully. Touchscreen displays angled at around a 45º tilt cause less self-reported discomfort and greater self-reported usability than either vertical or horizontal displays [278]. When participants are given a choice of several screen angles they tend to prefer an angle between 30 and 45º [50][279]. Gesturing with both hands rather than using a single hand appears to decrease subjective reports of discomfort when using touchscreens, especially for longer periods of usage [279]. However, more complex gestures, such as pinching to rotate or swiping, are associated with more joint activity than simple tap gestures, which may pose a higher risk of injury [276][280]. The ergonomic constraints of comfortable finger positions need to be considered alongside the display orientation when developing usable gestures and interfaces [281].

The height of a tabletop display strongly influences the ergonomic comfort of its use, with greater vertical distance between the head and the screen leading to increased discomfort and decreased usability [278]; thus, raised screens are preferred when standing and lowered screens are preferred when sitting. Duration of use is a particularly relevant factor for tabletop displays, as the downward angle of the head required for tabletop use can put significant strain on the muscles around the neck and spine [273][282]. Moreover, prolonged reading tasks on a tabletop display can increase perceived visual fatigue and required head movements, thereby adding to neck fatigue, relative to similar tasks performed on a laptop [282]. The method of input likewise plays a role in the ergonomic aspects of tabletop use, with mouse input generally preferred over direct inputs (e.g., touch or pen styli) for long-term use [80], but not necessarily for short-term use [86]. Trackball input may cause decreased discomfort in the hand than mouse input, but the trade-off is increased discomfort in the arms, neck, and shoulders [73]. Handwriting recognition using a pen stylus may alleviate some of the ergonomic concerns surrounding keyboard usage [283], but for the relatively small amount of text input expected to be involved in CRACCEN usage, the ergonomic advantages may make little difference in overall user experience.

It is worth noting that some of the ergonomic complications of tabletop displays may be alleviated by augmentation of the two-dimensional image into 3D. Virtual 3D information can be presented to HMD users at eye-level, rather than requiring them to look down at a tabletop display. Compared to vertical displays, the augmentation of tabletop displays with 3D AR HMDs and carefully designed gestural inputs helps to minimize fatigue by keeping users' hands in a relatively comfortable position between the shoulder and the waist [284][285]. However, mid-air interaction may be prone to cause arm fatigue [160][286] (c.f. [287], which showed no additional fatigue when users played a 2D game with mid-air gestures compared to a standard mouse). Other research has found that gestures performed in a virtual world as seen through VR HMDs resulted in higher levels of self-reported fatigue than the same gestures performed in the real world [288]. Methods for input amplification can reduce the strain of muscles from mid-air inputs [289].

VR and AR HMDs can also put additional strain on head and neck muscles [290][291][292][293][294] and cause discomfort and fatigue [294][295][296], though the amount of user-reported discomfort seems to depend heavily on the overall weight and weight distribution of the HMD [293][297][298]. In general, prolonged use is not recommended. A recent review contracted by DRDC suggests that AR HMDs such as the Microsoft Hololens2 should be generally safe for use in UWW, though ergonomic considerations suggest the duration of use be limited [297].

By comparison, 3D AR interactions are more physically tiring when performed via handheld devices rather than via HMDs [151]. Research has found significant neck, back, and arm strain following prolonged use of handheld devices [61][273][299]. Discomfort in the neck and back is especially pronounced when handheld devices are positioned in the lap while sitting [300], whereas holding a device aloft in one hand and performing touch actions with the other puts significant strain on the supporting wrist [301]. The ergonomic disadvantages of handheld devices may be alleviated by incorporating docking stands that support the device and allow for two-handed touch input at a comfortable height and angle relative to the user [302], but handheld AR devices generally need to be held aloft and moved to view a 3D scene.

6 Recommendations

The requirements analysis for CRACCEN outlined in Section 2 identified the need for at least one central 2D group display and the ability to visualize and interact with 3D information, given the 3D nature of the UWW environment. The possibility of combining multiple displays to accommodate the flexible transition between individual and group aspects of UWW task work was also discussed. Sections 4 and 5 presented a broad and interdisciplinary review of literature, in an effort to determine which display and input technologies are best suited to facilitate teamwork in the UWW environment.

A table summarizing the findings of the review is presented in Annex A, which facilitates direct comparisons between technologies. A full list of the references that guided the assessment of each technology is provided in the summary table and, for conciseness, is not reproduced in the written recommendations below. The recommendations drawn from the review are discussed in turn as follows:

1. A large tabletop 2D display should serve as the central group display;
2. Mounting hardware should be selected to allow the central display to convert flexibly between horizontal and vertical orientations, as needed; and
3. Optional additional devices could be networked with the central display to improve 3D visualization of the battlespace (i.e., AR HMDs) and to better support individual work that can subsequently be combined and shared on the central display (i.e., handheld devices or desktop workstations).

6.1 Large central tabletop 2D display

Working around a table is a familiar configuration for group discussion, deliberation, information sharing, and decision-making, and the intuitiveness of a multi-touch screen makes it easy for all users to contribute, whether simultaneously or in turn. This layout enhances communication and interaction quality in collaborative tasks and the ability to interact with the display from any edge greatly increases the simultaneous user capacity. The technology shares similarities with familiar and regularly used technologies such as desktop computers and smartphones, which will allow users to leverage existing knowledge frameworks and thereby reduce learning time. Knowledge frameworks for map reading, which often occurs on a horizontal surface, can also be leveraged for spatio-navigational planning and SA.

Direct touch is the ideal input method for 2D tabletop displays. This is particularly true when group work is required, because it allows users to easily follow the actions of their co-collaborators. Precision can be increased with pen styli, which can moreover be used for handwriting recognition as a text input method, though consideration for ship motion and moving peripherals may outweigh any added value from styli. Soft keyboards can be implemented for use by UWW teams as needed.

Special consideration for the ergonomics of use must be made during design phases, ensuring that important display menus are easily accessible and/or can be flexibly moved around the screen for easy access. Tabletop 2D displays have the potential to place strain on the neck and spine if positioned too low relative to the user, and touch-based interactions on large displays can cause muscle fatigue with extended use.

6.2 Flexible display angle

With the need to support mixed-focus tasks, flexibility would greatly benefit CRACCEN's usability. At a minimal extra cost for specialized mounting hardware, a collaboration-focused tabletop display can be converted into a presentation-focused vertical display on an as-needed basis. The vertical orientation would support more lecture-style communications; would facilitate briefings; and could stand as a background display to maintain

SA of tasks, platforms, and mission status when not actively being used for collaborative mission planning or execution tasks.

Special consideration for flexible interfaces must be made during design phases, as the orientation of the screen will greatly impact the type of information to be displayed and the organization of the interaction space. For example, reaching a menu in the top-left corner may be a trivial task for a user on the top edge of a tabletop display but a very taxing one for a user situated in front of a vertical display. The flexible system should be able to automatically recognize the orientation of the display and adjust output and interfaces accordingly. Although existing research provides some general guidelines (e.g., [38][39]), future research exploring specific naval use cases for different display orientations should guide CRACCEN interface design.

6.3 Optional AR HMDs and devices for individual work

Because the UWW environment is 3D, SA and mission planning are likely to benefit greatly from its 3D representation. Although both VR and AR HMDs support immersive interaction with virtual 3D objects, see-through AR HMDs provide better supports to communication and group work as well as a lower likelihood of cybersickness. AR HMDs could be available to CRACCEN users as optional aids for 3D visualization and interaction, and research suggests that effective collaboration and communication can be maintained at a high level even in instances where some collaborators wear HMDs and others do not.

Use cases for AR HMDs have already been explored in a variety of military settings, including navigation and SA in urban environments [303][304], army ground and vehicle warfighting scenarios [260], heads-up displays for air force pilots [260], and simulated training for high-risk scenarios [305]. To date little work has assessed the usability of AR HMDs in shipboard settings (but see [232][306]). Before development proceeds, research must be conducted to test the feasibility of AR HMDs in shipboard environments, as the effects of ship motion and vibration may hinder or preclude usability from the outset.

Although the focus of CRACCEN is on group work, individual UWW team members will still need to apply their individual expertise to the collaborative mission planning and decision-making tasks. Tablets or desktop computer systems could be available as optional supports to individual work, with networking capabilities to transmit information to the central group display during active mission planning tasks. The scientific literature does not currently provide clear guidelines for the suitability of one device (e.g., desktop or tablet) over the other for mixed-focus tasks, so both should be considered in initial research. Previous work combining technologies such as tabletops, tablets, 3D augmentation, and AR HMDs, for multi-user visualization in archaeology serves as a useful proof of concept: providing multiple methods for exploring and navigating a complex 3D environment can aid visualization and SA and thereby support interpretation and decision-making [307].

Designers of a flexibly coupled CRACCEN system will need to consider the best interfaces for individual work, how to transmit information between displays, and how transmitted information will be incorporated into the visualizations on the central group display. The trade-off between system flexibility and the additional practical complexity of integrating multiple devices (e.g., inter-device communication challenges, software updates, bandwidth limitations) must also be carefully considered.

6.4 Future research

Additional research is required to validate the above recommendations within the unique operational setting of shipboard UWW command teams of the RCN. Future research proposals for next steps in the development process are presented below in order of priority, although several lines of research may be conducted concurrently. In all proposed research cases, prototype development and user research are to occur in tandem, with each informing the other in an ongoing and iterative fashion. Continuous development and refinement of prototypes is assumed at all stages of the future research proposed.

6.4.1 Ideation studies for flexible displays

Thus far, this report has recommended the use of a central 2D tabletop display, the option to orient it vertically, optional AR HMDs for 3D information, and optional desktop or tablet devices for individual work. However, it is not clear which information and capabilities would best be presented on which display(s) and in which combination(s). An initial ideation study could have SMEs perform a brainstorming activity wherein they imagine conducting various mission planning, execution, and decision-making tasks on the different display options. Questions of interest in this line of research include: which tasks SMEs would like to be able to complete with each display option, which display option(s) they might look to when seeking particular information, what problems or issues they foresee with a given display, and what contribution they can imagine for their own role within the UWW team using each of the display options.

Building on the results of this initial ideation activity, follow-on research should assess design concepts and static mock-ups for interfaces on each display. Initial mock-ups and concepts would be developed from existing UX expertise, and subsequently presented for user testing and refinement. Questions of interest at this stage include: the perceived usability of the interface layouts presented, what changes SMEs might recommend to improve the layout of a given display, what changes SMEs might recommend with regard to the distribution of information or capabilities across displays (e.g., validating the initial ideation study), and how SMEs imagine themselves interacting with the displays. It is likely that several iterations of design concept development and user testing will be required, and it is possible that these initial studies will conclude counter to the recommendations provided in this preliminary report. It may be the case, for example, that existing desktop workstations available to the UWW team might prove sufficient for the capability requirements of the individual work aspects of CRACCEN, in which case further development of individual desktop or tablet interfaces need not proceed. In this way, the results of these studies will inform and constrain the direction of the additional research recommendations below.

Researchers might also consider employing VR to test design concepts with SMEs in a simulated shipboard environment. This would allow SMEs to experience and assess, at an early stage of development, the look and feel of CRACCEN within a virtual mock-up of their real work environment, rather than in a less realistic laboratory setting [308][309].

6.4.2 Testing prototypes for the central display

The next step recommended by the findings of this report is to develop a low-fidelity initial prototype for a CRACCEN tabletop, focusing on a usable 2D interface with a mock-up scenario that UWW team can work through as a group. Researchers can then use this prototype to test the usability of the system with SMEs and teams of SMEs [310].

Early iterations of prototype design and development may focus on high-level goals, and early testing may likewise involve relatively simple feedback methods, such as the Feature Capture Grid, which organizes feedback into likes, criticisms, questions, and ideas, in order to refine later design iterations [6].

Subsequent prototype iterations should incorporate increasingly detailed goals and specific capabilities. User testing of these later iterations could incorporate measures of task performance, usability (e.g., Tabletop Collaborative Usability Assessment [311]), verbal walk-throughs of system usage (e.g., [312]), post-scenario interviews, measures of workload and cognitive load (e.g., NASA-TLX [313]), and measures of team communication and cohesion. Eye-tracking measures may be incorporated to help improve interface design [314]. After a period of familiarization with the prototype, as recommended by [315], a formal evaluation of Task Technology Fit (TTF) should be undertaken to validate its fit to the task domain [316][317][318]. If the results of the ideation studies described above validate the usefulness of an optional vertical orientation, testing of this prototype should examine designs for this orientation as well.

6.4.3 Testing AR HMD and individual work prototypes

The feasibility of AR HMDs in shipboard environments must be tested at sea. Provided these tests demonstrate that AR HMDs can be safely used in the settings for which they are intended, development and testing of prototypes should proceed in much the same way as recommended for the central display: moving from high-level goals and simple feedback to tests of specific capabilities with a full suite of measures. Development should consider design heuristics in order to minimize ergonomic strain and maximize usability [319]. Initial evaluations may examine the AR HMD in isolation, but later research must incorporate the prototype of the tabletop display as well. SMEs can be individually tasked with providing initial high-level assessments and input to the use of AR HMDs for CRACCEN.

For collaborative tasks, the level of virtuality and immersion of a mixed reality system ought to be increased only as required by task demands, in order for users to maintain awareness of the physical space and collaborators [17]. The cycle of testing and development for AR HMDs needs to examine not only usability and TTF, but also a comparison of the value added by incorporating HMDs and 3D information [320], relative to any changes to the quality of task performance, cognitive load, teamwork, or communication.

If the results of the ideation studies described above validate the usefulness of tablets or desktop computers for individual work, testing of this prototype should likewise proceed from high-level goals and simple feedback to tests of specific capabilities with a full suite of measures. Initial evaluations may examine the individual work prototype in isolation, but later research must incorporate the prototype of the tabletop display as well. Because these devices are intended for individual work, initial evaluations can be conducted with individual SMEs.

Testing and development for individual work prototypes needs to examine usability, TTF, and a comparison of the value added by incorporating these additional devices, relative to any changes to the quality of task performance, cognitive load, teamwork, or communication.

7 Conclusions

The CRACCEN system is expected to revolutionize the way UWW is conducted within the RCN, with the potential to reshape not only how technology is used for UWW tasks but also how relevant tasks are distributed and completed among command team members. What the system should look like in order to accommodate this reimagined task and personnel space is a critical question, as the decisions made in early high-level design phases could constrain and define the nature of UWW in the future of the RCN. This report sought to identify the display and input technologies best suited for use by shipboard UWW teams by reviewing these technologies in relation to a number of high-level task requirements and constraints.

Initial requirements analysis presented in Section 2.3 suggested the need for at least one central 2D display screen, the ability to display and interact with 3D information, and the possibility of incorporating multiple displays for flexible mixed-focus work. This report reviewed multiple display technologies, input methods, and approaches to 3D augmentation, considering the suitability of the various technologies to both teamwork and the constraints of the UWW task environment.

Based on the results of an integrative literature review, the author recommends that a 2D tabletop display be adopted as the central display screen for CRACCEN, with flexible display orientations, optional AR HMDs to augment visualizations into the three dimensions of the UWW environment, and optional desktop or handheld displays for individual work that can be subsequently shared for planning and discussion at the central team display. However, characteristics unique to the UWW command team and their operational environment may influence the utility and usability of these technologies and technology combinations. Further research with SMEs must validate these technologies and test the usability of interface designs as prototype development proceeds.

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Annex A Integrative review summary

Table A.1: *A summary of the findings from the integrative review, assessing the extent to which a given display or input technology (rows) satisfies the criteria of interest for CRACCEN (columns).*

	Supports Individual Work	Supports Teamwork & Communication	Suitable to UWW Environment & Ergonomics	Comments
Central Display				
Desktop Display	High (baseline)	Low [33] [88] [155] Medium to high when combined with a group display [172]	Medium to High [273] [279] [282]	Ideal for individual work, currently employed widely on naval vessels. May be useful for the individual work aspects of mixed-focus collaboration.
Handheld Display	High [34] [35]	Low to Medium [34] [35] [88] [152] Medium to high when combined with a group display [172] [173] [174] [175] [176] [177] [178] [181]	Low to Medium [61] [179] [186] [252] [254] [273] [299] [300] [301] [302]	Good for individual work and okay for group work; but a number of ergonomic considerations. May be useful for the individual work aspects of mixed-focus collaboration.
Large Vertical Display	Medium [33] [38]	Low to Medium [33] [38] [39] [48] [49] [50] [52] [58] [178]	Medium [273] [274] [275] [278] [279]	Very good for leader-follower communications or static group displays, less ideal for equitable collaboration.
Large Tabletop Display	Medium [45] [46]	High [33] [34] [35] [38] [39] [40] [41] [42] [43] [44] [45] [46] [50] [51] [52] [53] [56] [58] [147] [178]	Medium [77] [273] [275] [278] [279] [282]	Ideal for collaboration and communication; some ergonomic and design considerations.

	Supports Individual Work	Supports Teamwork & Communication	Suitable to UWW Environment & Ergonomics	Comments
2D Input Methods[9]				
Direct Touch	High [59] [60] [61] [62] [63] [64] [65] [66] [67] [68] [69] [70] [76] [77] [78] [100]	High [79] [80] [81] [82] [85] [86] [88] [89] [90]	Medium [66] [76] [77] [80] [86] [246] [247] [248] [249] [251] [252] [253] [254] [257] [259] [276] [277] [278] [279] [280] [281] [287]	Ideal for collaboration; some ergonomic and environmental considerations.
Pen Styli	High [62] [69] [70] [71] [72] [100]	Medium [80]	Medium [80] [269] [270] [271] [283] (practical considerations)[10]	More precise than direct touch; may not be offset by pragmatic considerations for multiple pens/users but little research has looked at their use in collaborative tasks.
2D Mouse	High [59] [60] [61] [62] [63] [64] [65] [67] [73] [74] [75] [262]	Low [38] [80] [81] [82] [83] [84] [86] [89] [90]	Medium [73] [77] [80] [86] [246] [247] [248] [249] [252] [253] [259] [261] [262] [263] [264] [265] [267] [269] [270] [271] [287]	Not ideal for use with a tabletop, or for collaboration. Some ergonomic and environmental considerations.
Trackball	High [73] [75]	N/A	Medium to High [73] [246] [248] [250] [259] [266]	Not examined for teamwork, commonly used in shipboard environments.
Physical Keyboard	High [67] [91] [92]	Low (practical considerations)	Medium to High [247] [272] (practical considerations)	Ideal speed/accuracy and ergonomics. Less practical for collaborative work due to the need for physical keyboards.
Soft Keyboard	Medium to High [67] [91] [92] [93] [94] [96] [97] [98] [99]	Medium to High (practical considerations)	Medium to High [93] [95] [96] [97] [272]	Can be improved with gestures, haptic feedback, and dynamic resizing of keys. Multiple typists can work at once.
Handwriting Recognition	Medium to High [91] [99] [100]	N/A	Medium to High [283]	Not examined for teamwork; some ergonomic considerations.

[9] The assessments for input methods depend heavily on the display technology used. The ratings shown here assume the large horizontal display as the central display.

[10] Practical considerations denote additional issues that were discussed in the text but do not have references associated with them; these are typically common-sense or self-evident physical constraints that would not necessarily have been researched.

	Supports Individual Work	Supports Teamwork & Communication	Suitable to UWW Environment & Ergonomics	Comments
Speech Recognition	Medium [91] [101]	Low [91] [102]	Low (practical considerations)	Noise, jargon, and acronyms make it impractical for UWW environment; not ideal for multiple users.
3D Information				
Stereoscopic 3D Displays with Glasses	Low to Medium [103] [104] [105] [106] [107] [110]	Low (Medium*) [107] [111] [112]	Low [110] [190] [191]	Limited ability to interact with displays, not examined for teamwork. *Exception: Euclideon's multi-user glasses system
Auto-stereoscopic and Other 3D Displays	Low to Medium [29] [30] [113] [116] [157]	Low to Medium [109] [114] [115]	Low [190] [191]	Limited ability to interact with displays, with exception of volumetric displays. Little research on teamwork.
VR HMD	Medium to High [117] [125] [139] [159]	Low to Medium [117] [118] [120] [121] [122] [123] [124] [125] [126] [127] [128] [129] [130] [131] [139]	Low [186] [187] [188] [189] [191] [192] [193] [194] [195] [199] [205] [208] [211] [212] [213] [214] [215] [216] [217] [219] [220] [225] [226] [228] [229] [230] [231] [232] [233] [234] [235] [237] [238] [260] [286] [288] [289] [290] [291] [294] [295] (practical considerations)	Not ideal for co-located collaboration but may be good for remote collaboration. Ergonomic and environmental considerations. Cybersickness may be exacerbated in UWW environments.
AR HMD	Medium to High [136] [137] [139] [144] [151] [160] [164] [195]	High [31] [120] [126] [133] [134] [136] [137] [138] [139] [140] [141] [142] [143] [144] [145] [146] [147] [155] [166]	Medium [151] [160] [164] [191] [192] [195] [196] [197] [199] [201] [202] [206] [232] [236] [237] [238] [239] [240] [241] [260] [284] [285] [286] [290] [291] [292] [293] [295] [297] [298]	Ideal for collaboration; particularly strong combination with tabletop display. Some ergonomic and environmental considerations. Cybersickness may be exacerbated in UWW environments.
AR with handheld device	Medium to High [151] [154] [161] [162]	Medium [126] [129] [152] [153] [154]	Low to Medium [151] [273] [301]	Okay for collaboration, but a number of ergonomic considerations.
A rating is given for each technology's fit to each criterion: Low, Medium, High, or N/A in the event that insufficient evidence was available in the literature to support a rating. Relevant references to support each rating are provided in the row below each technology.				

List of symbols/abbreviations/acronyms/initialisms

2D	two-dimensional
3D	three-dimensional
AI	Artificial Intelligence
AOO	Area of Operations
AR	Augmented Reality
AS	Auto-stereoscopic
ASPO	Anti-Submarine Plot Officer
ASWC	Anti-Submarine Warfare Commander
C2	Command and Control
CANDID	Canadian Defence Information Database
CAVEs	Cave Automatic Virtual Environments
CO	Commanding Officer
COpsO	Current Operations Officer
COA	Course of Action
CRACCEN	Command Reconnaissance Area Coordination and Control Environmental Network
DRDC	Defence Research and Development Canada
DTIC	Defense Technical Information Center
FOpsO	Future Operations Officer
FTC-SS	Force Track Coordinator Subsurface
HGA	Hierarchical Goal Analysis
HMD	Head Mounted Display
IEEE	Institute of Electrical and Electronics Engineers
ORO	Operations Room Officer
RCN	Royal Canadian Navy
SA	Situation Awareness
SCS	Sonar Control Supervisor
SME	Subject Matter Expert
TG	Task Group
TTF	Task Technology Fit
UWW	Underwater Warfare
UWWD	Underwater Warfare Director
VR	Virtual Reality
WBE	Work Breakdown Element

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The Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) is a decision aid system being developed by Defence Research and Development Canada (DRDC) – Atlantic Research Centre to revolutionize the way the Royal Canadian Navy (RCN) conducts Underwater Warfare (UWW). This Scientific Report outlines the high-level goals and requirements of the CRACCEN system and reviews several fields of research in order to determine the appropriate candidate technologies for which to develop the system. A variety of potential display and input hardware technologies are evaluated with regard to both task requirements and characteristics of the UWW task environment. The results of this review suggest that a tabletop display capable of accommodating a group of simultaneous users be adopted as the central display for the CRACCEN system, with the possibility of using additional displays and display modes to augment the capabilities of the UWW team. Further research with Subject Matter Experts (SMEs) is recommended to validate the viability, usability, and added value of these displays, and to iteratively design interfaces that are well-suited to both the display type and the needs of the CRACCEN users.

Le Centre de recherche de l’Atlantique de Recherche et développement pour la défense Canada (RDDC) élabore actuellement un réseau environnemental de coordination et de contrôle de la zone de reconnaissance du commandement (CRACCEN). Il s’agit d’un système d’aide à la décision visant à révolutionner la façon dont la Marine royale canadienne (MRC) mène la guerre sous-marine (GSM). Ce rapport scientifique énonce les objectifs et les exigences de haut niveau du système CRACCEN et examine plusieurs domaines de recherche afin de proposer des technologies envisageables qui conviennent à son élaboration. Le rapport évalue une variété d’écrans d’affichage et de technologies matérielles d’acquisition de données en ce qui a trait aux exigences opérationnelles de même qu’à l’environnement opérationnel de la GSM. Les résultats de cet examen indiquent que l’affichage central choisi du système CRACCEN pourrait être sous forme de surface de table. Cet affichage permet d’accueillir plusieurs utilisateurs simultanément et offre a possibilité d’utiliser des écrans et des modes d’affichages supplémentaires afin d’accroître les capacités de l’équipe de la GSM. Il est recommandé de poursuivre les recherches avec des experts pour vérifier la viabilité, la convivialité et la valeur ajoutée de ces écrans, ainsi que pour concevoir des interfaces de manière itérative qui conviennent au type d’écran d’affichage et aux besoins des utilisateurs du système CRACCEN.