Bathymetric data visualization using extended reality in applied hydrographic operations environments

by

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Abstract

Over the last 100 years, significant advances have been made in morphometric technologies for underwater environments, leading to the availability of new three- and four-dimensional data products. However, the question remains whether the full value of these new datasets (with enhanced dimensionality) is being realized with conventional tools. The need to maximize the interpretation of multidimensional bathymetric spatial data is critical to the capabilities of hydrographic data analysis operations. Alongside new data products, new spatial interface technologies have emerged and matured that may significantly support the ability of a range of operational stakeholders to perceive and interpret multidimensional bathymetric data. Therefore, there is a need to investigate the potential of emerging tools and interfaces to improve bathymetric data visualization. This research considers the current status of 3D visualization methods and technologies in hydrographic work, and explores whether new 3D data representation methods and the capability of emerging interface technologies (e.g., mixed reality) may change how we experience, visualize, and interpret bathymetric data.

Keywords: 3D geo-visualization; augmented reality; bathymetric data; hydrography

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Chapter 1. Introduction

1.1. Overview

To situate this proposed research, it is necessary to review and summarize several pertinent fields of research, development, and scholarship. These include trends in methods to characterize bathymetric environments, trends in the form of geovisual outputs to map bathymetric data, current practices and emerging frontiers of bathymetric data visualization, and trends, challenges, questions, and opportunities within these domains.

The earliest depth measurement instruments in water were the sounding rod and the lead and line, which involved lowering the tool over the side of a ship and measuring the wet end when it reached the bottom (Kemp and D'Olier, 2016). These techniques were used for thousands of years until single-beam echo sounding emerged in the 1920s, improving efficiency and accuracy and increasing data visualization, processing, and analysis complexity. This method estimated depth based on the acoustic pulse travel time and the average speed of sound in water. In 1960, narrow beam echosounders and multibeam swath bathymetry enhanced underwater mapping efficiency (Vilming, 1998). Swath bathymetry extended across-track sounding coverage, mapping 100 percent of the surveyed area and substantially increasing data size. Despite the advent of the multibeam echosounder, single-beam echosounders remained popular for hydrographic surveys due to the high cost of early multibeam models. However, improvements in multibeam echosounders made them cheaper, more efficient, and more accessible, becoming the primary source for bathymetric data acquisition (Lekkerkerk, 2018).

In the mid-1990s, high-resolution multibeam echosounders provided calibrated acoustic backscatter values co-registered with each bathymetric sound (Dartnell and Gardner, 2004). Backscatter, once considered noise, began to provide valuable information such as seabed type (Ponce, 2019). In the past three decades, underwater acoustic data acquisition has been complemented by Light Detection and Ranging (LIDAR) and satellite-derived bathymetry (SDB) (Churnside, 2013; Ponce, 2019). These methods are mainly used in shallow, clear waters, typically in coastal environments where ship-based systems are challenging and dangerous (Wölfl *et al.*, 2019).

Today, various platforms and technologies can be combined to acquire bathymetric data in different environments. Echo sounders are used on vessels ranging from small boats to large ships, as well as Unmanned Surface Vehicles (USVs), Remotely Operated Underwater Vehicles (ROVs), and Autonomous Underwater Vehicles (AUVs). Aircraft, both manned and unmanned, use LiDAR technology, and satellites obtain data through remote sensing. These technologies generate bathymetric data in point cloud format, delivering high-definition seabed representations but increasing data processing time. Cloud-based storage is increasingly used to distribute high-definition bathymetric data products (Amirebrahimi *et al.*, 2019).

The hydrographic offices evolved their chart production in the late 1990s and early 2000s. Their focus was to build central database systems that allowed the distribution and creation of paper, raster, and Electronic Navigational Charts (ENC) at will and simultaneously (Ponce, 2019). These databases could also add object and attribute data to the traditional bathymetric data, stimulating the use of Geographic Information Systems (GIS) as part of the hydrographer's toolset (Lekkerkerk, 2018).

Over the years, the application of Geographic Information System (GIS) theory and technology in the marine field has fallen behind compared with the land field, with still less hydrography (Duan, Wan and Luo, 2021). The IHO S-57, against its original design, led to hydrographic survey data being exclusively used for electronic navigation chart (ENC) production (Alexander *et al.*, 2007). Since 2005, the hydrographic community, led by the International Hydrographic Organization (IHO), has been developing the IHO S-100 Universal Hydrographic Data Model. This new model aims to enhance its predecessor, the IHO S-57 Transfer Standard for Digital Hydrographic Data, by addressing previous limitations and better integrating marine geographic information into global information systems (Ward *et al.*, 2008; Duan, Wan and Luo, 2021).

The need to follow the standards and comply with the requirements established by the IHO S-57 has significantly influenced the hydrography community to follow the 2D paradigm in which displayed marine information resembles traditional paper nautical charts, even in the most recent chart-plotters. The influence of these standards and the logistics of confirming them may be one of the reasons why different methods and interface options for viewing bathymetric data, such as new 3D interactive visualization interfaces, are not being exploited and taken advantage of. In other words, the entire creation and later use of nautical charts continue to be essentially visualized in 2D displays, occasionally employing aids of perspective renderings of data on screens like pseudo-3D representation. Alternatively, perhaps there has not yet been an adequate empirical study of the capabilities of these emerging geovisual interfaces to enhance perception, task performance, or communication. Such evidence (positive or negative outcomes) would better justify maintaining current data visualization practice or might reveal quantifiable value and benefits to migrating hydrographic data visualization into 3D/4D visualization interface environments.

A recent survey found that high-resolution bathymetric data, usually obtained through multibeam echosounders, is commonly used for geological mapping, seafloor physical characterization, hydrographic charting, and navigation (Amirebrahimi *et al.*, 2019). Processing this data is a significant bottleneck in updating nautical charts due to increasing data volumes and the need to clean spurious data and identify features. Despite precise sensors and modern acquisition systems, incorrect points often arise in geospatial data. Automatic algorithms like the Combined Uncertainty and Bathymetry Estimator (CUBE) have reduced cleaning time, but detailed analysis still requires manual inspection (Calder and Mayer, 2003; Makar, 2017; Wölfl *et al.*, 2019). Analyzing complex submerged features, such as shipwrecks, demands thorough inspection and understanding. Non-immersive tools can take hours or days to complete such analyses. Studies have shown that virtual reality can enhance the speed and quality of bathymetric data analysis (Stevens and Butkiewicz, 2019). Classifying submarine features after processing can be arduous, requiring significant interpretive skill. Most processing software uses non-immersive tools, which may not provide the best perceptual affordances for hydrographic data users. Some studies have explored automating the production of nautical charts, but a human review is still necessary to avoid navigation accidents (Masetti, Faulkes and Kastrisios, 2018; Pe’eri and Dyer, 2018; Rustomji, 2018; Stevens and Butkiewicz, 2019; Wölfl *et al.*, 2019).

Advances in nautical chart methods, hydrographic surveying, and bathymetric mapping have transformed how we characterize underwater environments. While 3D and 4D data are common, fully experiencing and utilizing this data remains challenging. Emerging spatial interface technologies offer new ways to perceive, explore, and communicate underwater environments through immersive experiences.

Mixed Reality (MR), which combines real and virtual elements, has been particularly effective. MR environments, including Augmented Reality (AR) and Augmented Virtuality (AV), are used in various applications like virtual surgery, vehicle simulations, and cultural heritage (Gutiérrez Alonso, Vexo and Thalmann, 2008; Skarlatos *et al.*, 2016; Hedley, 2017; Bleier *et al.*, 2019; Wang *et al.*, 2020). MR can represent and explore complex geographic phenomena, supporting the development of users' mental models of geographic spaces. Research by Shelton and Hedley (Hedley *et al.*, 2002; Shelton and Hedley, 2002) demonstrated that AR interfaces enhance the perception of 3D spatial data by combining everyday perceptual contexts with virtual data.

Further exploration of AR/MR interfaces in bathymetric data visualization is needed to understand their potential for improving perception and interpretation. The hydrography community primarily uses 2D methods for viewing bathymetric data, resembling traditional paper nautical charts, even in modern chart-plotters. While the Universal Hydrographic Data Model standards offer more data, better filtering, and customization features, they still rely on 2D display representations (Kuwalek, Maltais and Journault, 2012; Jonas, 2021). Non-immersive interaction techniques, such as the Slope or Hill-shading technique, have been popular for map displays and continue to improve, allowing manipulation and navigation in 3D environments using standard hardware (Kennelly, 2009; Jankowski and Hachet, 2015).

Charts and maps are crucial for navigation and understanding spatial relationships, but their 2D representation poses cognitive challenges (Lütjens *et al.*, 2019). Research indicates that 3D tasks are better performed with 3D interfaces (Ware and Jessome, 1988; Mattheiss, Schrammel and Tscheligi, 2011). Traditional methods may not provide the best understanding of bathymetric data, suggesting that new methods and interfaces, such as Extended Reality (XR), could be more effective. XR technologies, including virtual, mixed, and augmented reality, offer innovative ways to connect data-driven representations to real-world aspects, transforming how people understand and utilize geospatial data (Çöltekin *et al.*, 2020).

1.2. Research problem

The whole process of creating or updating nautical charts relies on the visualization of 3D data, mainly bathymetric data. The idea is to translate underwater reality into paper. The data collected about the ocean and rivers describes a 3D world, but a chart is a 2D representation.

Hydrographers and nautical cartographers are challenged to understand and analyze features like sunk ships, rocks, channels, slopes, and half-buried trees using 2D interfaces (computer screens).

For the reasons outlined in the background section above, there is a need to investigate the degree to which 3D spatial interface technologies (particularly mixed reality) can support meaningful perception, interpretation, and use of 3D hydrographic data sets. Building data visualization prototypes is an essential part of demonstrating potential solutions. However, even more important is to gather direct empirical evidence of the perceptual, interpretative, and task performance outcomes of bathymetric data use mediated by 3D spatial interfaces. This is essential to inform and guide the future directions of hydrographic data visualization.

1.3. Research questions

A) Do “conventional” versus AR hydrographic data visualization platforms result in different perceptual outcomes of data for users?
   1. Are there significant differences in the ability to identify spatial features in hydrographic datasets?
   2. Are there significant differences in the ability to perceive spatial relationships between features in hydrographic data sets?

B) Are task performance outcomes different when performed in each of the “conventional” versus AR hydrographic data visualization platforms?
   1. Are there significant differences in the accuracy of tasks performed in “conventional” versus AR hydrographic data visualization platforms?
   2. Are there significant differences in the speed of tasks performed in “conventional” versus AR hydrographic data visualization platforms?

C) Are AR interfaces (and their affordances) suitable for integration into everyday visualization in hydrographic data analysis?
   1. Which affordances of the AR interfaces do users perceive to support a hydrographic office's data operations best?
   2. Which characteristics of AR-based data visualization do users perceive to undermine hydrographic data visualization or to be challenges that need to be overcome?

1.4. Research objectives

The objectives of this research are to:

- Review the current state of research literature related to the visualization (representation) of bathymetric data.
- Assess and quantify the variety of approaches to visualize bathymetric landscapes and their distribution across research and professional practice domains.
- Identify progress and trajectories in bathymetric data visualization and summarize the existing challenges and opportunities.
- Through prototypes, demonstrate and comparatively assess the capability and affordances of conventional and AR interfaces to visualize identical hydrographic data.
- Empirically evaluate and compare user perception (feature identification, interpretation, and relationships) and task performance (accuracy, speed) with hydrographic datasets.

1.5. Thesis organization

This thesis consists of four chapters: an introduction, two main chapters written as stand-alone papers submitted to peer-reviewed journals, and a conclusion. These papers collectively introduce current practices within the hydrographic community, discuss emerging technological methodologies to supplement and enhance national hydrographic service production, and present workflows developed to achieve the research objectives.

Chapter 2 provides a literature review to identify and document trends in the technologies and interfaces used for hydrographic visualization. Initially, it summarizes the platforms and methods currently employed to visualize bathymetric data in nautical cartographic production. Subsequently, it discusses the themes related to the potential utility and implications of emerging tools and interfaces for enhancing bathymetric data visualization based on reported outcomes in the selected literature.

Chapter 3 builds on the research presented in the previous chapter by examining hydrographic practitioners' ability to perceive the spatial structure and relationships of 3D bathymetric visualizations using tabletop augmented reality (AR) interfaces compared to conventional desktop computer monitors. A two-phased experiment was conducted to compare the performance of two groups of participants, utilizing a tabletop AR interface and a desktop monitor to view and perform a series of perceptual and interpretation tasks with identical visualizations of bathymetric datasets. Participants engaged in spatial perceptual tasks (position, geometry, relationships) followed by data interpretation tasks. By analyzing user performance in these tasks across each interface, this study explores the potential of emerging tools and interfaces to enhance bathymetric data visualization compared to traditional devices.

The final chapter concludes the thesis by discussing the significance of the research presented in Chapters 2 and 3 and further identifying possible future directions for research in immersive methodologies and technologies for improving bathymetric data visualization.

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Chapter 2. Bathymetric data visualization – A review of current methods, practices, and emerging interface opportunities[1]

2.1. Abstract

Advances in 3D surveying and data processing encourage the hydrographic community to consider the limitations of existing visualization methods and the opportunities of emerging interface technologies to view bathymetric data. This paper aims to identify and document trends in the technologies and interfaces used for hydrographic visualization. First, it aims to summarize the platforms and methods currently used to visualize bathymetric data in nautical cartographic production. Second, based on reported outcomes in the selected literature, themes in the potential utility and implications of emerging tools and interfaces to improve bathymetric data visualization are discussed.

2.2. Introduction

Among the vast number of sciences related to the study of oceans, rivers, and lakes, hydrography is defined by the International Hydrographic Organization (IHO) as the branch of applied sciences that deals with the measurement and description of the features of the seas and coastal areas for the primary purpose of navigation and all other marine purposes and activities. It includes (but is not limited to) offshore activities, research, protection of the environment, and prediction services (IHO, 2005). In other words, hydrography has been historically responsible for gathering the data required for reproducing submarine relief, making its visualization possible.

Hydrographic activities, science, and data products revolve around improving the representation of the underwater landscape in order to allow better characterization, analysis, and interpretation. Deeply intertwined with this are exploratory, confirmatory, and communicative visualization actions. Elucidating the nature of bathymetric

[1] A version of this chapter has been published in *the International Hydrographic Review* under the co-authorship of Nick Hedley.

environments is the primary reason for these data's existence and drives their production and quality control phases. Since such data visualization is intrinsic and fundamental for hydrographic practice (analytical visualization, interpretation, collaborative decision-making, communication, and dissemination), it is essential to review how the workflows that result in hydrographic data visualizations differ and how these differences may produce similar or distinct representations or operational outcomes.

Data visualization is essential to determining veracity and quality during all phases of bathymetric data generation—from acquisition to the end of its processing. Visualizing bathymetric data can occur at any stage of its lifespan, whether in the raw data acquisition phase, the data processing phase, or when data are already validated and archived in a database. Viewing the bathymetric data allows flexibility in the forms and interfaces used.

2.2.1. Review considerations and strategies

This study reflects upon the technologies and interfaces used to visualize bathymetric data during hydrographic surveys and store it in existing repositories at national hydrographic offices. It takes into account the different types of equipment, software, and technologies used for the acquisition, processing, and storage of bathymetric data, assuming the period after the release of the fifth edition of IHO S-44 Standards for Hydrographic Surveys (IHO, 2022), which took place in 2008.

The search for articles used as a reference for this review was carried out using a group of keywords, complemented by articles published by journals focused on all aspects of hydrography and associated subjects, such as The International Hydrographic Review (IHR) and Hydro International. Studies written in English and Portuguese were considered.

The following terms and keywords were used separately and in combination to search for articles relevant to this review: 2D visualization, 3D visualization, augmented reality, bathymetric data, bathymetry measurements, cartography, data acquisition, data processing, geovisualization, interfaces, hydrography, marine environment, mixed reality, nautical cartography, pseudo 3D, true 3D, virtual reality.

2.2.2. Organization of Review

This article divided the bathymetric data visualization forms into three groups according to the bathymetric survey phase. In this way, the first group will have the methods of visualizing the data during its acquisition; the next group will show the forms of visualization during the data processing and analysis phase; finally, the ways of visualizing the already processed and stored data in databases, usually applicable on survey design, charting and reporting data. In the sequence, alternative (immersive) bathymetric data visualization methods are presented, exploring those not yet fully incorporated into the most popular methods.

2.3. Trends in the technologies and interfaces used for bathymetric data visualization

The protocols and standards established by the IHO, under the requirement set out in the International Convention for the Safety of Life at Sea (SOLAS) and other international regulations, have been decisive in guiding the directions taken by the international hydrography community. Created in 1921 and headquartered in Monaco, the IHO, the former International Hydrographic Bureau, has reached its 100 anniversary with nearly 100 member states represented by their respective hydrographic offices (HO) (IHO, 2022). Since its creation, the IHO has provided a forum for Member States and International Organizations to connect, address relevant issues, and develop collaborative programs. Today, the IHO takes a leadership role in the hydrographic community in the Ocean Decade, supporting and facilitating the improvement of ocean knowledge delivery, both qualitatively and quantitatively (Jonas, 2021). In this way, the collaboration of members of the hydrographic community, facilitated by the action of the IHO, results in how hydrographic surveys have been carried out. The IHO, as an intergovernmental organization, assists in implementing the enhancement and expansion of hydrography infrastructure through technical standardization, directly or indirectly influencing trends in the technologies and interfaces used for bathymetric data visualization.

2.3.1. Trends and current practice in data visualization during acquisition

The visualization of bathymetric data during its acquisition may or may not be performed depending on the platform's characteristics and acquisition method used. In some cases, the availability of physical space and whether the platform works autonomously can limit or even prevent data visualization during acquisition.

In contemporary practice, multiple approaches have been taken to acquiring bathymetric data using different platforms, equipment, and methods. Acquisition methods have been diversifying since 1970, but over the last two decades, significant growth in ocean mapping was noticed, encompassing different platforms, equipment, and acquisition principles (acoustic, optical, and radar) (Smith Menandro & Cardoso Bastos, 2020; Ferreira et al., 2022). Underwater acoustic data acquisition, the primary and most used method to date (Kenny et al., 2003; Smith Menandro & Cardoso Bastos, 2020), has been supplemented with other significant sources of bathymetric data, such as Light Detection and Ranging (LIDAR) and satellite-derived bathymetry (SDB; Churnside, 2013; Ponce, 2019), Airborne Derived Bathymetry (ADB) and Synthetic Aperture Radar (SAR; Wiehle et al., 2019). LiDAR and SDB have been mainly used in shallow clear waters, generally in coastal environments, where it could be difficult and dangerous to gather bathymetric data using ship-based systems (Wölfl et al., 2019). Coverage, spatial and temporal resolution, and data type vary among a diverse range of bathymetry acquisition systems (Kearns et al., 2010). In all cases, the chosen sensor must be associated with a positioning source to ensure the data is spatially referenced for integration with other data sources and prepared for use in a Geographic Information System (GIS; Holland et al., 2016).

While dedicated to the safety of navigation, nautical charts are compiled from data originating from multiple sources and different systems and sensors using a range of procedures (Molchan, 2017), especially in shallow or remote areas (Mavraeidopoulos et al., 2017). The subitems below present the current practices for acquiring bathymetric data, divided by the operating principle of each sensor (acoustic sensors, air, and spaceborne remote sensing), and how these data are visualized while they are acquired.

Trends and current practice in data visualization during the acquisition of bathymetric data using acoustic sensors

The technological advances in remote sensing using electromagnetic radiation and artificial satellites have improved and direct land surface mapping, providing high-definition surveys on Earth and other astronomical objects (Smith & Sandwell, 1997; Bolton et al., 2020). However, the incredible power of water absorption and attenuation of electromagnetic radiation makes it impossible to use these technologies to survey the seabed in deep areas and under turbid water (Allouis et al., 2007; Leder et al., 2020). In other words, mapping almost three-quarters of the Earth's surface area, covered by oceans, lakes, and rivers, must rely on equipment and sensors based on acoustic energy such as sonar.

The primitive techniques used by mariners to measure depth were replaced by single-beam echo sounding in the 1920s, which constituted a notable improvement in efficiency and accuracy and increased data visualization, processing, and analysis complexity. The single-beam echosounder, a type of sonar (short for SOund NAvigation and Ranging) used as research equipment, employs the physical properties of the acoustic pulse in the aquatic environment to measure depth values. In 1960, the advent of the narrow beam echosounder and the principle of multibeam swath bathymetry further expanded underwater mapping efficiency (Vilming, 1998). Unlike single-beam sonar, which uses just one transducer to map the seafloor, a multibeam sonar sends out multiple sonar beams simultaneously in a fan-shaped pattern that covers the space directly under the ship and out to each side. The Multibeam Echosounder (MBES) has become the sonar technology most used by hydrographic offices to carry out their surveys (Brown et al., 2019; Smith Menandro and Cardoso Bastos, 2020), followed by the Single Beam Echosounder (SBES) and the Sidescan Sonar (SSS; Ferreira et al., 2022).

Ships, ranging from small boats to great research vessels, with or without crew, are still the most common platform for adequately applying acoustic remote sensing systems and performing large-scale seafloor mapping (Connon, 2021; Ferreira et al., 2022). Since, in recent years, there has been immense enthusiasm for using autonomy and robotics in the hydrographic survey industry, organizations' preferred solution for improving ocean mapping and increasing survey capacity has been achieving force multiplication by combining crewed and uncrewed vessels (Fig. 1; Holland et al., 2016; Van Wegen, 2022).

Figure 1 Hydroceanographic Research Vessel "Vital de Oliveira" can conduct hydrographic surveys with its two hydrographic research boats and an ROV (Brazilian Navy).

Depending on their size, research vessels usually have sufficient space to install a data acquisition system and an office or cabinet to accommodate the system operator (Fig. 2). From these control rooms; operators can monitor the data acquisition systems in real-time by previewing the data on the console screens. Under these conditions, the data is in a generation phase before the raw data and can be presented in different graphic forms, depending on the resources available in the acquisition software. A common practice is to place the system in acoustic pulse emission mode but not turn on data recording when the intention is to only visualize a surface, for example, during a survey planning phase.

Figure 2 Data acquisition control room (Brazilian Navy).

It is also ubiquitous for large ships transporting smaller research platforms, such as hydrographic boats and Unmanned Underwater Vehicles (UUV), which are divided into two kinds: Autonomous Underwater Vehicles (AUV) and Remotely Operated Underwater Vehicles (ROUV or just ROV; He et al., 2020), and Autonomous Surface Vehicles (ASV).

The smaller the vessel, the smaller the space available for the operator, who usually also serves as the boat operator during the survey. For example, in the case of watercraft and inflatable boats, the reduced space and lack of shelter from the external environment reduce the number of resources available for monitoring and controlling the acquisition system. Suppose the system operator also drives the vessel; the operator’s attention is divided into three non-equal parts (Fig. 3). The first and biggest one is oriented to navigation, which concerns the safe conduction of the boat through the research lines (Ternes et al., 2008). Secondly, monitoring the system, checking if the system is working correctly and if any alert message or error is generated automatically. Lastly, a small part of the operator's attention is on the system's control. In short, the possible ways of viewing bathymetric data on small vessels are the same as those performed on larger vessels. The difference is the space and operators available to interact with the acquisition systems. ROVs, also seen as underwater tethered robots controlled from the surface, emerged as platforms to support industrial activities in the underwater environment (Macreadie et al., 2018).

Figure 3 Interior of the hydrographic small boat carrying out multibeam surveying (Institudo Hidrografico).

ROVs can serve many uses (Wu, 2017), whether hull inspection (Waszak et al., 2022) or sampling from the sea floor (Mazzeo et al., 2022), usually performing the work of human divers in cases where diver safety is not guaranteed. As a research platform, it allows the installation of various sensors and equipment, like echo sounders' transducers, video cameras, and others, depending on their size and structure (Huvenne et al., 2018; Macreadie et al., 2018). However, ROVs rely on one or more qualified human operators and the support of a launch and control platform (Wu, 2017; Huvenne et al., 2018).

The main difference in an acquisition made using the ship is that the transducers are installed on the ROV, not the ship's hull. Moreover, the transceiver and the acquisition system's monitoring and control console remain on board the vessel. In this sense, the visualization of bathymetric data during the acquisition phase using ROV is not far from what is done using a research ship since both the sensors and the acquisition systems are the same.

In line with the new development trend of automating the acquisition, transmission, and processing of bathymetric data and reducing costs and time spent to carry out hydrographic surveys, autonomous systems, mainly the ASV and AUV, currently, stand out (Wölfl et al., 2019). After being pre-programmed with mission parameters, autonomous systems (AUV and ASV) can collect data without needing a human controller (Huvenne et al., 2018). With the development of increasingly efficient batteries (Reader et al., 2002) and the availability of sensors, these vehicles can cover large areas, navigate safely, and even avoid obstacles (Wynn et al., 2014). However, despite the automaticity of autonomous Vehicles, they still depend on support platforms for their launch and recovery, especially in places far from the coast (Wynn et al., 2014; Ferreira et al., 2022). Autonomous systems are generally similar to ROVs in the visualization of bathymetric data acquisition. Although the echo sounder is installed in vehicles, a human controller can monitor the system if there is communication with the vehicle (Giodini et al., 2016). However, due to limited communications capabilities, some autonomous operations require their vehicle to be recovered before accessing data stored internally (Figure 4; Holland et al., 2016).

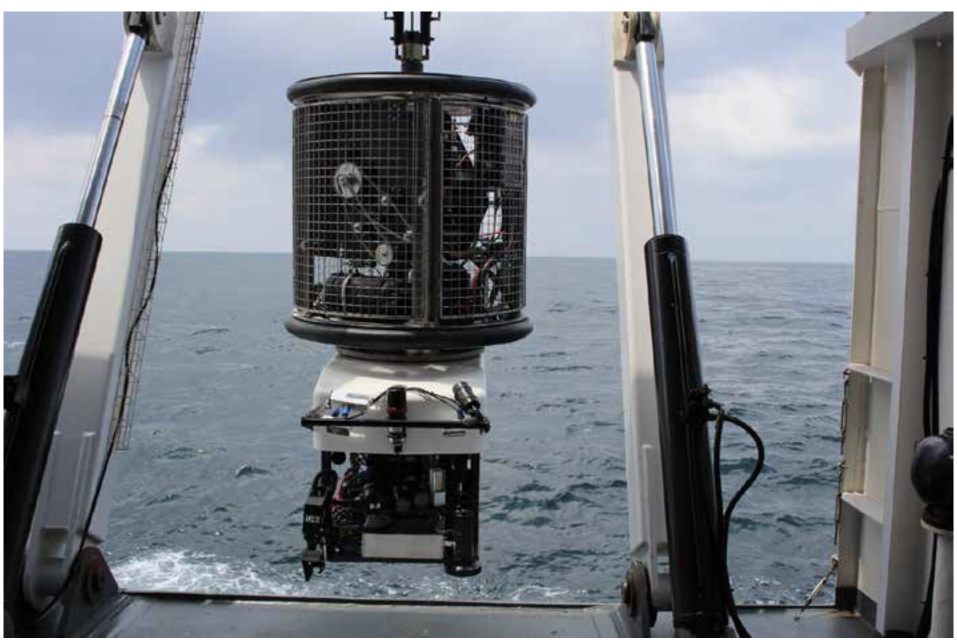

Figure 4 ROV Launch and Recovery System with winch and A-Frame. (Brazilian Navy).

Usually, manufacturers offer packages that include software for data acquisition and processing and equipment and sensors. However, it is possible to use software developed by other manufacturers. Some companies like HYPACK have developed software for the hydrographic and dredging industries for decades. Their software is one of the world's most widely used hydrographic software. Along HYPACK (acquired by Xylem Inc. in 2015), major hydrographic acquisition software market players include Stema Systems, Teledyne Marine, Chesapeake Technology, QPS, Ifremer, Eye4Software, and EIVA (Value Market Research, 2021).

In the context of work conducted in the hydrographic offices, where the surveys carried out in their areas of jurisdiction are processed, a considerable volume of projects need to be verified and potentially used for the preparation or updating of nautical documents, the use of software reliable and established in the market becomes essential. Thus, hydrographic offices use the software developed by leading companies to respond to the great demand for work.

Trends and current practice in data visualization during the acquisition of bathymetric data using air and spaceborne remote sensing

Despite the high attenuation of electromagnetic waves in water, the remote sensing method of applying multispectral bands can be employed in bathymetric mapping, depending on the water's clarity (Roberts, 1999). Air and space-borne remote sensing are especially effective in coastal environments where collecting bathymetric data with ship-based systems in shallow water is substantially more time-consuming and hazardous than collecting deep-water data. Moreover, exploiting satellite imagery has proven to be an alternative technique for quickly collecting bathymetric data, offering significant advantages to planning and executing hydrographic activities (Panayotov, 2018).

In this context, depths can be measured using two system types: passive type, which measures only the natural energy naturally available on the submerged bottom (spectral response bathymetry), and active type, which uses lasers to measure the distance to the seabed. Remote sensing of bathymetry also falls into non-imaging and imaging methods, where imaging methods base the water depth estimation on an image's pixel values. In contrast, using single or double waves, non-imaging detects the distance between the sensor and the water surface/sea floor (Gao, 2009). For example, light detection and ranging (LiDAR) and Radar Altimetry sensors are classified as active type and non-imaging methods of remote sensing of bathymetry. In contrast, synthetic aperture radar (SAR) uses an imaging method despite being an active type that transmits microwave signals and then receives the signals that are returned, or backscattered, from the Earth’s surface. Lastly, Satellite Derived Bathymetry (SDB) is a technique based on the empirical, semi-analytical, or analytical modeling of light transmission through the atmosphere and the water column. The imagery data processing consists of atmospheric correction, air-water interface corrections, and the implementation of inverse optical models (Mavraeidopoulos, Pallikaris, and Oikonomou, 2017). SDB sensor is of passive type and uses an imaging method (Hartman et al., 2017).

There is great flexibility in platforms for installing remote sensing equipment, including planes, helicopters, drones, satellites, and even small boats or ships. For example, Unpiloted Aerial Vehicles (UAV) have provided a cost-effective alternative for remote, small, and localized Airborne Lidar Bathymetry (ALB) surveys, leading lidar manufacturers to develop lighter, more compact sensors suitable for this market (Quadros & Keysers, 2018). Depending on the platform used for a hydrographic survey, there may be an operator controlling the acquisition system from within the platform itself, such as an airplane, there may be an operator controlling the survey platform from a remote location, such as a drone, or even the absence of a controller, as is the case with satellites and autonomous platforms.

The acquisition of bathymetric data, using equipment on board crewed aircraft or unmanned platforms, in general, has the same concerns: to perform the flight safely and travel the planned route to cover the entire desired area. In this way, similar to acquiring bathymetric data on offshore platforms, the visualization of the data being acquired is not intended to analyze the features presented but its integrity. Bearing in mind that reliable analyses are always performed on processed data, not raw data, the acquisition phase mainly seeks to ensure that the data is complete and readable.

2.3.2. Trends and current practice in bathymetric data visualization during processing

Regardless of the equipment or platform used to acquire bathymetric data, these raw data need to go through some general processing stages (Wlodarczyk-Sielicka and Blaszczak-Bak, 2020), which usually include corrections, such as noise removal, filtration process (Zhang et al., 2016), applications of other complementary data for calibration, data reduction (Wlodarczyk-Sielicka et al., 2019), generation of digital terrain model (DTM), so that analysis and reliable information could be extracted. MBES, for example, despite being a highly developed sensor, even with careful and engaged data acquisition that follows all rules and recommended guidelines, its collected data may contain undesired errors due to various external factors (Le Deunf et al., 2020; Wlodarczyk-Sielicka & Blaszczak-Bak, 2020; Šiljeg et al., 2022). The same also applies to airborne bathymetric LiDAR (ABL). The objective of airborne laser echo signal processing is to estimate the distance between the receiving system and the target once the received echo waveform usually contains multiple noises or “false signals” caused by environmental interference and the system’s circuit (Guo et al., 2022).

If the forms and equipment used to acquire bathymetric data are very diverse, the same cannot be said about the range of methods and techniques used to process them. Usually, each equipment manufacturer implements and offers patented software for processing data acquired by their equipment (Parnum & Gavrilov, 2011; Guo et al., 2022)., but multiple companies develop software aimed at processing various formats of bathymetric data, such as HIPS and SIPS from Teledyne Geospatial (Teledyne, 2023), HYPACK MAX from HYPACK Xylem (Xylem, 2023), LiDAR Survey Studio from Leica (Leica, 2023), NaviSuite from EIVA (EIVA, 2023), among others. It is observed that any hydrographic processing software shares similar core processing operations (Boers, 2016), which some software offers some complementary resources, such as geodetic support functionalities, types of data visualization (fly-throughs support, area-based 3D view, and editing, 4D support), but also some potential limitations, such as types of data format the software can import and export, minimum software’s system requirements (Langhorst, 2022). Besides, some bathymetric data processing software offers automated processing features (Wölfl et al., 2019), which are even recommended by the IHO S-44 standard (IHO, 2022), such as the CUBE (Calder & Mayer, 2003; Makar, 2017), the algorithm that most of the commercially available automatic cleaning methods rely on (Ferreira et al., 2019; Le Deunf et al., 2020). Smaller firms and research groups have explored low-cost solutions outside the proprietary commercial software processing programs, such as open-source software (Zhang et al., 2016; Bobich, 2020). These trends in bathymetric data processing are likely driven by the fact that the hydrographic community meets the international norms established by the IHO, which dictates the standards of how a hydrographic survey should be done as a whole (Wlodarczyk-Sielicka & Blaszczak-Bak, 2020), leading the market to develop products that adhere to these requirements.

To illustrate how bathymetric data processing from hydrographic surveys has been done using data processing software available on the market, raw bathymetric data acquired by an MBES system can be taken as an example. In general, data about the platform and the equipment used in data acquisition are entered into the software, informing its characteristics, such as dimensions, positioning, and manufacturer data. The raw data are also inserted into the software; it is necessary to convert the file format depending on the software. Other complementary and essential data for correcting the raw data are loaded into the software, such as sound speed profiles, navigation data, and attitude of the acquisition platform and tide heights. The software combines all entered data, and the degree of uncertainty of these values is calculated. The spurious data is cleaned, which can be done manually or using an algorithm, such as CUBE. Finally, quality control is performed. The whole process can be performed using a laptop computer or even a desktop and its peripherals.

In the hydrographic offices' context, verifying the detection and cleaning of erroneous soundings while processing bathymetric data is crucial since the final objective is to update bathymetric information on nautical charts, guaranteeing the safety of navigation (Le Deunf et al., 2020). Another critical factor is the speed with which new nautical document updates are available (Pe’eri & Dyer, 2018). This situation becomes more explicit when one observes that the number of sensors available to conduct surveys, the increased use of autonomous platforms, and the volume of data generated are all factors that have pushed ocean mapping into the Big Data age (Holland et al., 2016). Faced with an increasing volume of bathymetric data coming from different sources of data acquisition, including non-traditional sources (Pavic et al., 2020), the national hydrographic offices have encountered a situation in which they need to optimize the verification and compilation of the data received, either by research carried out by the institution itself or by that belong, or by third parties, in order to quickly feed the databases with new entries, which may help update nautical documents (Ponce, 2019). Multiple efforts are underway to accelerate the processing, analyzing, and leveraging available raw data to generate data product updates (Wölfl et al., 2019). The search for a procedure that achieves maximum productivity with minimum wasted effort invariably involves using data processing software available on the market, developed precisely for this purpose. In a production line context, viewing bathymetric data during processing often takes advantage of visualization capabilities available in the data processing software. This leaves little room for alternative methods not integrated with the software adopted by established standard production procedures.

2.3.3. Trends and current practice for viewing post-processed data in National Hydrographic Offices' databases

Hydrographic surveys can be carried out both by private companies and by government agencies in order to obtain valuable bathymetric data for application in several areas of knowledge, such as geology, oceanography, archaeology (Janowski et al., 2021), environment, and a growing variety of uses fundamental to understanding the planet's phenomena, as well as for the development and structuring of coastal and port areas. Lastly, bathymetric data are critical for establishing the limits of the extended continental shelf under the United Nations Convention on Law of the Sea (Alberoni et al., 2020; Suárez-de Vivero, 2013). Although using bathymetric data for navigation purposes is exclusive to national hydrographic offices, their use for other activities, such as scientific research, is usually authorized. Several national offices, such as the Brazilian Directorate of Hydrography and Navigation (DHN) and the Canadian Hydrographic Service (CHS), provide some of their stored bathymetric data. In a global context, some organizations, such as The Nippon Foundation, promote the international sharing of bathymetric data, such as the GEBCO Seabed 2030 Project, in the sense of the general development of the ability to explore and critically understand ocean and seafloor processes (Mayer et al., 2018).

For the specific case of using bathymetric data for the construction or updating of nautical documents, such as nautical charts, hydrographic surveys are generally submitted to the appreciation of the national hydrographic offices, which have their policies for the verification and use of the data received (Fig. 2). In any case, all data received, regardless of being effectively used for editing a nautical document, are archived as long as they are valid. In this way, it is common for national hydrographic offices to become large repositories of bathymetric data, compiling datasets in a variety of formats and from multiple new and historical sources from surveys carried out in their jurisdictional waters in robust databases (Maia et al., 2017).

It has been a common practice among hydrographic offices to store processed bathymetric data in databases, usually managed by software developed for this purpose (Schwarzberg, 2019). The format of the files stored in the databases may vary from office to office, depending on the local data management policy and the system used. However, converting the files to the default XYZ file format is usually possible, ensuring smooth integration with all domain-specific software. In this condition, the data integrate a library, which gathers all valid and available data to be used for the production of marine products, such as nautical charts for example, as well as to be used as reference sources for hydrographic research or even from other areas of study.

The data visualization in the database can vary considerably, depending on the reasons for using it. Large geographic areas containing data from several hydrographic surveys can be visualized for research or work planning requiring these dimensions. On the other hand, small areas within a single survey can also be visualized in the case of a specific study or verification. For example, as part of assessing a possible anchoring area, someone could verify the presence of any unnatural feature, like parts of sunk ships, planes, or helicopters, that would make the area unsuitable for anchoring.

During the nautical cartographic production process, after a new bathymetric surface is added to the database, a check is made if it fills a previously empty area, overlaps with old surfaces, originated from old surveys already stored, or both situations at the same time (Le Deunf et al., 2023). This verification is essentially done visually by displaying the surfaces of a given location on a display device, usually a flat computer screen. In cases where new and old bathymetric surfaces overlap, a comparison is made in order to verify whether the new data present better resolution and a significant amount of alterations that justify an update of the nautical document associated with the geographic area (Kastrisios et al., 2023; Le Deunf et al., 2023).

Finally, hydrographic offices have adapted to the actual wave of digitization of hydrographic information, also known as “hydrospatial” (Ponce, 2019), using the IHO S-100 data model (Alexander et al., 2007; Ward et al., 2008; Schwarzberg, 2019), which will result in a considerable expansion of digital data services. The model explores the technique of visual two-dimensional overlaying of constantly new layers of information (Jonas, 2023).

2.3.4. The increasing significance of 3D data and its visualization and the emergence of interface technologies that may support transformative information experiences

3D visualization technologies have increased in use and significance and have been considered a promising tool for various applications in many applied fields (Juřík et al., 2020), including geovisualization (Bleisch, 2012), geomorphology (Wang et al., 2020), crisis management (Lonergan et al., 2015; Rydvanskiy & Hedley, 2021), indoor navigation (Lochhead & Hedley, 2019), underwater mining operations (Bleier et al., 2019), visibility analysis (Lonergan & Hedley, 2016), and others.

As mentioned before, in hydrography, modern data processing software has offered features that allow the geovisualization of a set of bathymetric data from different perspectives, contributing to the perception and understanding of spatial information. Among the perspectives offered, the option of creating, visualizing, and manipulating digital images of 3D objects and scenes is considered of great potential for exploratory and data analysis 3D geovisualization purposes (MacEachren & Kraak, 2001, Bleisch, 2012), where expert users (hydrographers) focus on recognizing important features or patterns in a data set, taking advantage of highly interactive features. Interaction and navigation in 2D and 3D displays have become essential to 3D geovisualization as they aim to gain insight, allowing the user to overcome occlusion or examine the dataset from different angles, where the 3D impression is received through rotation of the model on a computer screen (Lütjens et al., 2019).

In the context of spatial knowledge acquisition and cognitive perspective, previous studies (Hedley et al., 2002; Shelton & Hedley, 2004) discussed the benefits of using specific mechanisms offered by immersive environments, such as Virtual Reality and Augmented Reality, since these environments exploit 3D visualization technology.

Moreover, in the field of cognitive psychology, there are many studies on the perceptual and cognitive processes in augmented reality, exploring the differences between the binocular and monocular presentation of stimuli (Dempo et al., 2022). Besides, different forms of 3D visualization may stimulate distinct types of human behavior and cognitive responses; for example, they can affect human sensorimotor and interaction approaches, cognitive processing, and, eventually, human performance (Juřík et al., 2020).

Pseudo-3D (monoscopic) versus true-3D (stereoscopic) visualization

The abbreviation ‘3D’ is usually used generically and can refer to different meanings. The types of 3D visualizations depend on the principles on which they are built and the technologies used to display them, the two main types being 3D visualizations are pseudo-3D (also known as 2.5D or weak 3D) and the less common real 3D (also known as strong 3D) visualizations (Kjellin et al., 2010; Buchroithner, 2012). Real 3D visualizations employ monocular and binocular depth cues (especially binocular disparity cues) to achieve a stereoscopic vision (Juřík et al., 2020). Pseudo-3D depictions are visualized perspective-monoscopically on a two-dimensional display surface or planar media, such as on a monitor screen, and are not autostereoscopic. It requires projection of the 3D geometry, which usually means perspective distortion (Seipel, 2013). Figure 5 illustrates the conceptual design of 2D, pseudo-3D, and true-3D visualization conditions.

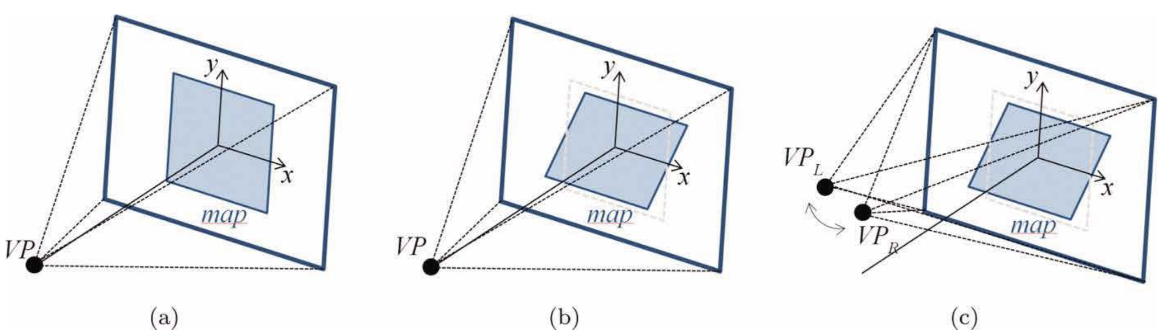

Figure 5 (a) 2D map display in the zero-parallax plane; (b) 3D tilted map using pseudo-3D perspective; (c) 3D tilted map using strong perspective and stereoscopic viewing. (Seipel, 2013)

Evolving display types offer the opportunity to shift away from traditional 2D displays and explore alternative ways to interact with bathymetric data.

As technology and equipment that provide immersion become more accessible, more study projects are beginning to explore applications of some degree of extended reality in bathymetric data acquisition and processing and nautical product upgrades (Jonas, 2023). The term ‘extended reality’ (or XR) has been adopted as an umbrella term for virtual, augmented, and mixed reality (VR, AR, MR) immersive technologies, which refers to technologies and conceptual propositions of spatial interfaces studied by engineering, computer science, and human-computer-interaction (HCI) researchers. The delineation between these terms remains fuzzy as XR expresses a spectrum of VR, AR, and MR (Çöltekin et al., 2020). One example is the evaluation of editing 3D point clouds using Immersive VR to speed up multibeam sonar data cleaning of spurious values during bathymetric data processing (Stevens & Butkiewicz, 2019). VR has also been used to display 3D nautical charts for navigation track control during hydrographic data acquisition, aiming to increase the spatial and situational awareness of the helmsman and allow intuitive and quicker decision-making in running desired tracks for hydrographic surveys (Ternes et al., 2008). One of the first examples of Augmented reality (AR) applied to hydrographic data use involved a first-generation Hololens mixed reality device on the bridge of a vessel – with basic observations of whether it simplified or expedited the regular updating process of nautical paper charts with new information, and to view chart update locations and their respective locations on the paper chart (Kokoszka et al., 2018). While this initial work is helpful, additional work – using formal assessment of spatial perception and task analysis – is needed to empirically determine emerging interface technologies' capabilities to support and enrich hydrographic data use.

However, in research carried out in national hydrographic offices, the usual software for processing and manipulating bathymetric data uses traditional 2D planar media, including computer monitors and presentation room projector screens. Despite the hydrographic community successfully migrating from an analog to an electronic model, the information continues to be presented in two-dimensional ways (Jonas, 2023). That said, this scenario tends to remain unchanged since the hydrographic community is currently interested in technological development revolving around robotics, autonomous and uncrewed systems, machine learning, and artificial intelligence, all topics that will not render hydrographic surveyors obsolete but considerably reduce their direct activities (Van Wegen, 2022).

Despite the observation that immersive visualization is currently not present at all or used only to a minimal degree in bathymetric data, research, and analysis indicate that the application of AR and VR in hydrographic office workflow may offer significant benefits, including a faster and more accurate understanding of the portrayed situations when compared to their 2D counterparts. After all, immersive environments like VR and AR offer fundamental parameters for true 3D visualization (Hedley & Lochhead, 2020; Lochhead & Hedley, 2021). For example, the degree of freedom, degree of perception, and degree of immersion are highly correlated with the spontaneity of perception regarding the third dimension. (Knust & Buchroithner, 2014). Moreover, since the visual perception of normal-sighted persons is stereoscopic, it makes sense to use modern technologies to render geovisualisations for truly three-dimensional viewing (Knust & Buchroithner, 2014). Furthermore, geospatial problems and questions are often 3D, yet data is traditionally illustrated on 2D surfaces, like maps or computer monitors, posing cognitive challenges for users (Lütjens et al., 2019). Since hydrographic data survey technologies inherently generate 3D data (Bleisch, 2012), tools that provide 3D data processing and deliver truly 3D-dimensional data visualization experiences to support interpretation should be considered.

Several authors studying spatial interpretation tasks have independently investigated the relative value of true 3D visualizations compared to 2D visualizations. However, more and sustained empirical evaluation of the potential of these interface systems to support bathymetric data perception and task performance is needed.

2.4. Conclusion

Throughout this article, we observed that, despite their specificities, the world's hydrographic services and offices have many characteristics in common. National hydrographic institutions generally establish their bases on land and equip their data acquisition platforms, usually ships, with the acquisition systems available on the market. They plan and execute their hydrographic surveys based on IHO standards. They process their data again according to IHO standards and using the processing systems available on the market. The processed data are stored in databases, used to publish nautical documents, and distributed or commercialized. As can be seen, uniformity is a strong characteristic of the hydrographic community, perhaps driven by a mutual commitment to comply with the norms and standards established by IHO. Most likely because it has representatives of different nationalities in its working groups, the IHO publishes, updates, and openly discusses the paths to be followed in hydrography with its members. At the same time, uniformity benefits a production line, such as elaborating and updating nautical charts. This characteristic can also lead to the suppression of the initiative to try to use alternative technologies and innovate the process that has been done. Mainly when the existing standards are particular and detailed, and the current method is well-evaluated and considered satisfactory.

Although current data analysis interfaces are relatively successful, thanks to their development over time, there is still a need for innovation in minimizing human error and reducing time-consuming processing. With advances in cognitive science and psychology comes a better recognition of the strengths and limitations of human perception and the natural abilities of our brains. New immersive interfaces should use this knowledge and be designed to support the strengths and minimize the limitations to reduce errors made by analysts.

The traditional representation method may not provide the best understanding of bathymetric data. Alternatively, methods and interfaces, such as Extended Reality, could be more efficient. Extended Reality can provide new ways to connect data-driven representations directly to real-world aspects. Therefore, virtual, mixed, or augmented reality technologies could offer unparalleled experiences with significant potential to transform how people understand and utilize geospatial data, providing new visualization and interaction methods (Çöltekin et al., 2020). Since previous studies (Torres et al., 2013; Juřík et al., 2017; Juřík et al., 2020) indicate that the advantages and disadvantages of applying true-3D visualizations are still open to discussion in various fields, especially regarding the interactivity factor, further research should explore interactive and advanced geospatial tasks that may strongly affect the cognitive processing of the stimuli.

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Chapter 3. An Empirical Assessment of Tabletop Augmented Reality Interfaces for Analytical Hydrographic Data Use versus Conventional Desktop 3D Visualization[2]

3.1. Abstract

This paper explores hydrographic practitioners' ability to perceive the spatial structure and relationships of 3D bathymetric visualizations in tabletop augmented reality (AR) interfaces versus similar 3D data visualized using conventional desktop computer monitors. A two-phased experiment was carried out to compare the performance of two groups of participants, where both used a tabletop AR interface and a desktop monitor to view and perform a set of perceptual and interpretation tasks with identical visualizations of bathymetric datasets.

A group of 42 hydrographic data analysts used a set of test datasets in two interface environments (desktop monitor versus tabletop AR). Participants engaged in a set of spatial perceptual tasks (position, geometry, relationships), followed by a sequence of data interpretation tasks. Their performance in perceptual and interpretation tasks using each interface was assessed in terms of accuracy and speed at identifying and classifying features of the displayed dataset. Our findings were that the AR interface may offer advantages regarding spatial perception and depth of understanding.

3.2. Introduction

Hydrography is experiencing one of the most agitated periods in its history, where the demand for more accurate and fast-updated bathymetric data is growing (Pe'eri and Dyer, 2018; Kastrisios *et al.*, 2023). Driven by ambitious projects such as the "Nippon Foundation – GEBCO Seabed 2030 Project (Mayer *et al.*, 2018)", which has mapped about 20% of the world's ocean floor and seeks to complete the whole ocean mapping by the year 2030, multiple technologies have been developed and incorporated into hydrographic surveys (Ferreira *et al.*, 2022), increasing the level of complexity and

[2] A version of this chapter has been submitted to *IEEE Oceanic Engineering* under the co-authorship of Nick Hedley.

workload. At the same time, the hydrographic data production systems have faced the challenge of migrating to new international standards, the IHO S-100 Universal Hydrographic Data Model, that will require straightforward access to high- quality digital geospatial information to support marine activities (Ponce, 2019; Jonas, 2021). As new sensor technologies and data outputs have emerged, so too have a range of spatial interface technologies and research. Technologies, such as any degree of Mixed Reality (Hedley, 2017), offer significant potential to provide users of geospatial data with new ways to perceive, explore, communicate, and experience underwater environments through interface technologies that can both immerse us in data and, through them, immerse us in the spaces they represent (Çöltekin *et al.*, 2020).

3.2.1. Current practice in hydrographic data visualization and interpretation

Many national governments are signatories to the International Maritime Organization's International Convention for the Safety of Life at Sea (SOLAS) (IMO, 1974), reflecting their endorsement of responsibilities and objectives to accomplish the safety of life at sea by publishing nautical charts, publications, and other support services. Therefore, each national Hydrographic Office (HO), or national hydrographic service, is responsible for creating and updating their countries' official nautical documents and policies on how this work is carried out (Maia, Florentino and Pimentel, 2017). For this, the HO receives data from hydrographic surveys carried out by institutions directly linked to the offices and by researchers authorized to conduct research in their jurisdictional waters. The data obtained are usually filed in the office's database, a source of information for editing nautical documents (National Centers for Environmental Information, 2024).

Each HO has policies and directives on evaluating and using bathymetric data (Maia, Florentino and Pimentel, 2017). Some choose to use automatic systems and algorithms (Calder and Mayer, 2003; Pe’eri and Dyer, 2018; Wölfl *et al.*, 2019), but it is common practice for experienced hydrographic analysts to verify it in some offices (Le Deunf *et al.*, 2020). Visualizing the data is one of the main ways the analyst verifies, manipulating the data set through peripherals such as a keyboard and mouse and using computer screens to display the images. The verification predominately consists of repetitive manual tasks seeking to identify failures in acquiring raw data and processing errors that alter the acquired bathymetry (Masetti *et al.*, 2022). During verification, the analyst uses one or more specific software for bathymetric data processing, ordinarily available on the market (Value Market Research, 2021). These programs, developed by companies based on the guidelines published by the International Hydrographic Organization (IHO), offer various data verification tools (Langhorst, 2022). This way, traditional 2D planar media was consolidated, adding pseudo-3D visualization features and using computer monitors and presentation room projector screens.

3.2.2. Evolving technologies in hydrographic data use

If, a few decades ago, the methods of acquiring and processing bathymetric data were limited to a few options, in recent years, hydrographic practices, led by a worldwide effort to develop systems, sensors, and alternative techniques for depth measurement, have increasingly seen the emergence and expansion of automated and autonomous technologies (Smith Menandro and Cardoso Bastos, 2020; Masetti *et al.*, 2022). This growth in the production of bathymetric data has led hydrographic surveys to generate enormous amounts of information from multiple sources (Holland, Hoggarth and Nicholson, 2016; Jonas, 2023), which requires adequate processing, analyzing, and managing (Wlodarczyk-Sielicka and Blaszczak-Bak, 2020; Le Deunf *et al.*, 2023). Software for acquiring, processing, and managing bathymetric data has developed significantly to adapt to the reality of activities carried out in hydrography, seeking to respond to current demands and bringing efficiency (Langhorst, 2022).

3.2.3. New types of interfaces and hydrographic office work-flow

Interface technologies are essential as they act as the conduit through which users interact with and interpret complex data visualizations. These technologies determine how information is displayed and influence user engagement, comprehension, and decision-making processes. Empirical studies on their potential influence are crucial because they provide evidence-based insights into how different interface designs affect user perception, cognitive load, and overall usability. By understanding these impacts, designers can create more effective and intuitive visualizations that serve diverse user needs, ultimately enhancing the ability to derive meaningful insights from data (Few, 2024).

In bathymetric data analysis, interface technologies are fundamental in enabling the effective visualization and interpretation of complex underwater terrain data. High-resolution bathymetric maps, essential for marine navigation, environmental monitoring, and resource management applications, rely heavily on sophisticated visualization tools. These tools must present data in an accessible and intuitive manner, allowing users to explore and manipulate the data effectively.

Research has shown that advanced data acquisition methods, such as single-beam and multi-beam echo sounders (SBES), significantly enhance the accuracy and efficiency of underwater mapping. These technologies produce detailed and reliable bathymetric data, but their complexity necessitates robust interface technologies to accurately manage and interpret the information. For instance, multi-beam echo sounders (MBES) are favored for their ability to cover large, high-resolution areas. However, they require sophisticated interfaces to process and visualize the vast data collected (Araujo and Hedley, 2023; Li *et al.*, 2023).

Empirical studies on these technologies are crucial to understanding their impact on user perception and usability. Effective interface design can reduce cognitive load and improve the accuracy of data interpretation, which is particularly important in fields that rely on precise and timely information. By continually evaluating and refining these technologies based on empirical evidence, we can enhance the overall effectiveness of bathymetric data analysis, ensuring that users can make well-informed decisions.

Different methods and interface options exist for viewing bathymetric data; however, the hydrography community continues to follow the 2D paradigm in which displayed marine information resembles traditional paper nautical charts, even in the most recent chart-plotters. Hence, for some years, there have been discussions about presenting hydrographic information more familiarly, similar to how video games are given, in three dimensions or employing AR (Jonas, 2023). The emergence and development of new data products and new spatial interface technologies may significantly support the ability of a range of operational stakeholders to perceive and interpret multidimensional bathymetric data. Therefore, there is a need to investigate the potential of emerging tools and interfaces to improve bathymetric data visualization.

3.2.4. Objectives of this research

This exploratory research aims to investigate and quantify the potential changes in perception and task performance when transitioning the visualization of raw bathymetric data from a standard interface to a tabletop AR interface. This study employs exploratory research methods to uncover underlying patterns, relationships, and insights that may not be immediately evident. Compared to traditional methods, this research aims to identify critical factors and variables that influence user experience and performance by examining how AR visualization impacts users' understanding and efficiency in interpreting bathymetric data. The findings from this study will provide a foundation for more targeted and conclusive research, contributing to the development of improved visualization techniques for bathymetric data interpretation.

3.2.5. Visualization Interfaces: Rationale for choice of interfaces

In recent decades, the hydrographic community has successfully migrated its nautical products from analog to electronic models, producing them consistently and standardized based on the standards published by the IHO (Ponce, 2019). The databases could also add object and attribute data to the traditional bathymetric data, stimulating the use of Geographic Information Systems (GIS) as part of the hydrographers' toolset (Lekkerkerk, 2018).

However, these digital variants have mainly followed the printed models, maintaining that the presentation is two-dimensional (Jonas, 2023). In other words, the entire creation and later use of nautical charts continue to be essentially visualized in 2D displays, occasionally employing aids of perspective renderings of data on screens like pseudo-3D representation. Over time, the influence and limitations of the IHO standards, especially the IHO S-57 Transfer Standard for Digital Hydrographic Data, may be one of the reasons why different methods and interface options for viewing bathymetric data, such as new 3D interactive visualization interfaces, were not being exploited and taken advantage of (Alexander *et al.*, 2007; Ward *et al.*, 2008; Duan, Wan and Luo, 2021).

Since hydrographic data survey technologies inherently generate 3D data (Bleisch, 2012), tools that provide 3D data processing and 3D data visualization are vital to support interpretation. Modern data processing software has offered features that allow the visualization of a set of bathymetric data from different perspectives, taking advantage of interactive features, where the 3D impression is received through rotation of the model on the computer screen (Lütjens *et al.*, 2019), contributing to the perception and understanding of spatial information.

Augmented Reality (AR)

AR is a technology in which information is superimposed onto the real world directly in front of observers. Essentially, AR 'augments' views of reality by integrating virtual computer-generated content into the user's view of their physical environment. This allows users to interact with digital elements as if they were part of the real world, providing an enriched and interactive experience (Hedley, 2017).

AR interfaces are made possible by three main ingredients: tracking of real-world surroundings, registration of virtual objects to the real world (using computer vision and other methods), and rendering virtual content into views of the real world - made visible by a range of display technologies (Hedley, 2017). Tracking is crucial for 3-D applications involving user interaction with virtual spaces, as it provides information about the location and orientation of objects and users in real 3-D space. This ensures accurate correspondence with their positions in virtual spaces. Low-latency tracking is essential for high-performance virtual environments where real-world positions and actions match their virtual equivalents. In AR, tracking determines the positions of real-world objects, allowing digital objects to be registered to them. This can be done using fiducial markers and computer vision software, where unique patterns are recognized, and their orientation and position relative to the camera's viewpoint are calculated. This enables the AR software to render virtual objects at the correct location and alignment, a method commonly used in tangible AR (Hedley, 2017).

AR systems could use monocular, binocular, and biocular presentations (Kitamura *et al.*, 2014, 2015). A binocular system presents the information using two optical trains, one for each eye. In contrast, a biocular system has only one optical train, and the aperture is large enough to simultaneously observe both eyes.

AR capability can be achieved through combinations of sensors and cameras integrated with display and interaction devices, computer vision software, and thoughtful interface design. Different designed implementations can offer advantages for specific applications (Van Krevelen and Poelman, 2010). Advances in camera, GPS, accelerometer, and display technologies in mobile devices have led to using tablets and smartphones as AR displays (Hedley, 2017). Smartphones and tablets are among the most accessible devices, using their cameras and screens to display AR content (with the metaphor of an AR ‘lens’), thus bringing AR applications to a broad audience. Head-mounted displays (HMDs) can arguably provide a more immersive experience by filling the user’s entire field-of-view (FOV) with augmented views of reality. Optical see-through HMDs allow users to see the real world directly with digital content superimposed, making them ideal for applications requiring high interaction with the physical environment, such as medical or industrial uses. Video see-through HMDs, which capture the real world with cameras and display the combined content on screens within the headset, offer better integration of digital elements but may encounter latency issues. Improvement and evolution of wearable Virtual Reality (VR) devices have increased considerably over the past few years. Devices such as the Meta Quest 3 can be loaded with standalone VR and AR software to enable unwired VR and AR experiences. Furthermore, progress in camera and computer vision technology has resulted in increased performance with inside-out tracking by these headsets (for position and context as a basis for registration), enabling users to use the same headset for immersive VR and ‘pass-though AR and ‘pass-through mixed reality (MR), using the outward-facing cameras on these devices.

Rationale for choice

This research aims to fill a gap in the ocean data research community. While early work has been done to integrate AR with seafloor data visualization, (Palmese and Trucco, 2008) work to study whether such interfaces support effective hydrographic practice is almost non-existent to date.

Comparing tabletop AR interface visualization with conventional desktop 3D monitor visualization is essential for understanding the advantages and limitations of each approach in bathymetric data interpretation. Traditional desktop 3D monitors offer high-resolution displays and familiar interfaces, while tabletop AR interfaces potentially enhance spatial awareness and interaction by integrating digital information with the physical environment (Jo *et al.*, 2021; Turhan and Gümüş, 2022). This comparative analysis aims to determine whether the immersive and interactive nature of AR provides significant improvements in user perception and task performance. Identifying these differences is crucial for developing practical visualization tools that enhance data interpretation accuracy and efficiency, ultimately leading to better decision-making in fields relying on precise bathymetric data.

This comparison is the first step toward a comprehensive and systematic empirical evaluation of mono versus stereo AR and stereo AR versus stereo VR. By establishing a baseline understanding of how AR interfaces compare to traditional 3D monitors, we can design more effective experiments to explore the nuances of stereoscopic visualization. Subsequent studies will delve into the impact of depth perception, spatial awareness, and user interaction on task performance and perception, providing a holistic view of these advanced visualization technologies. The insights from this research will inform the development of optimized visualization tools tailored to specific applications and user needs, enhancing the effectiveness and usability of AR and VR systems in various professional and scientific domains.

3.3. Empirical Methods and Materials

3.3.1. Used Methods

This study employed two 3D visualization interfaces with distinct visual cues to investigate their effects on subjects' data perception. The motor aspects of interaction with 3D visualizations were not considered in this project, as the processing and analysis of bathymetric data—routinely performed by hydrographic analysts—require substantial manipulation of the viewpoint. In other words, bathymetric data are not processed or analyzed from a static, single perspective. Since the participants' motor activity, such as actions for navigating the terrain, was not measured, we utilized typical control devices, such as a computer mouse, to interact with the visualizations.

The study involved the following steps: Participants navigated to a designated survey website (surveymonkey.com). They read and agreed to a consent form outlining the survey's terms, their rights and protections, and contact information for inquiries. Participants completed a survey comprising 52 questions, which included checking boxes, ranking options, and providing short answers, using both desktop and mobile device-based data visualization tools.

The recorded data included participants' responses to the online questionnaire. This data was securely stored in an SFU-supported facility, protected by passwords and encryption. The information collected during the study was kept confidential and used solely for research purposes. No raw survey data was shared with commercial partners, though graphical summaries of aggregated data might have been included in academic publications. No participant names were collected, ensuring no participants were identifiable. The study did not collect any identifying information about participants, ensuring their privacy was maintained. There were no foreseeable risks to participating in this survey. Participants performed simple tasks involving viewing and interpreting 3D data visualizations while sitting at a desk in DHN's regular office, using everyday devices such as a typical desktop computer, smartphone, or tablet with a camera. Participation in the study was voluntary and unpaid.

The experiment was divided into two identical phases, Interface DT and Interface AR, with the execution order alternating between the groups involved. The first group performed tasks using the standard desktop interface (Interface DT) and the augmented reality interface (Interface AR). Conversely, the second group performed the same tasks but started with Interface AR before using Interface DT. Given the use of two datasets in the research, two questionnaire versions were created (A and B), with the order of model use reversed. Consequently, the experiment was conducted in four distinct configurations: Group A, Group B, Group A (inverted), and Group B (inverted).

After consenting to the form, the volunteer is invited to complete a background/operational survey. Following a familiarization period, the experiment begins using one of the interfaces. The volunteer identifies and compares pre-selected points from visualized bathymetric data. A researcher monitors each task, measuring the time it takes to complete it and recording the volunteers' answers during the AR interface phase. During the DT interface phase, the volunteers answer the questions independently.

Upon completing all tasks, the volunteer is invited to answer a post-experiment questionnaire regarding their experience. Then, the volunteer visualizes another 3D model using the other interface and performs identification and comparison tasks with different pre-selected bathymetric data points, manipulating the device to obtain the answers.

After completing all tasks with the second interface, the volunteer is invited to answer a second post-experiment questionnaire about their experience. Upon completing both stages of the experiment (desktop and AR interfaces), the volunteer responds to a final reflective questionnaire comparing the two stages (Figure 6).

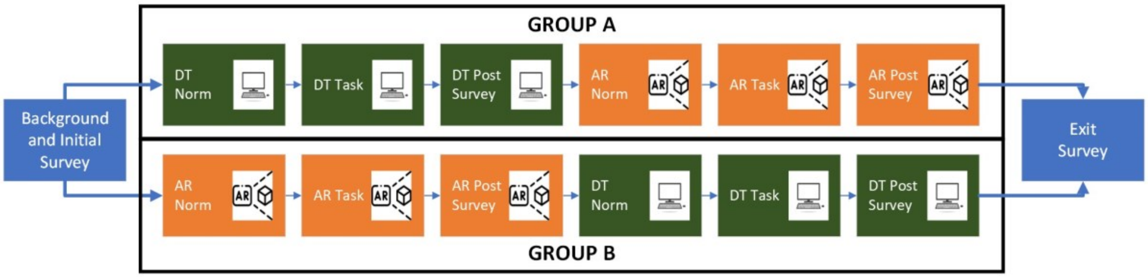


Figure 6 **Experiment layout**

3.3.2. Bathymetric Data Used

The experiment used bathymetric data collected from two sunken ships, MV GB Church and HMCS Mackenzie, near Sidney, in October 2019. Using a Kongsberg EM2040P MkII multibeam echosounder aboard the CSL Heron survey boat, owned by the Canadian Hydrographic Service, several survey lines were acquired in each ship's area. The settings included high-density beam spacing, dynamic dual swath, 300 kHz frequency mode, high-resolution water phase data, and a survey speed of around 6 knots (Gomes de Araujo, 2024). These datasets provided the foundational background for the experimental tasks. Both datasets were employed for both interfaces but were only used once per subgroup. Consequently, each subgroup observed a change in the dataset when transitioning from one interface to another.

The raw data, in point cloud format (.txt), were imported into CloudCompare software for preparation (Figures 7a and 8a). The preparation process involved selecting and coloring specific point groups to capture the attention of the experiment participants (Figures 7b and 8b). Excess data surrounding the ships' hulls, such as seabed data, was excluded to reduce the total number of points and lighten the files (Figures 7c and 8c). Additionally, it was necessary to reduce the resolution of both models to accommodate Sketchfab.com's AR visualization limitations. The Sketchfab.com platform was also utilized to convert the point cloud models (in LAS file format) to AR file format (GLTF), which was subsequently used in the experiment.

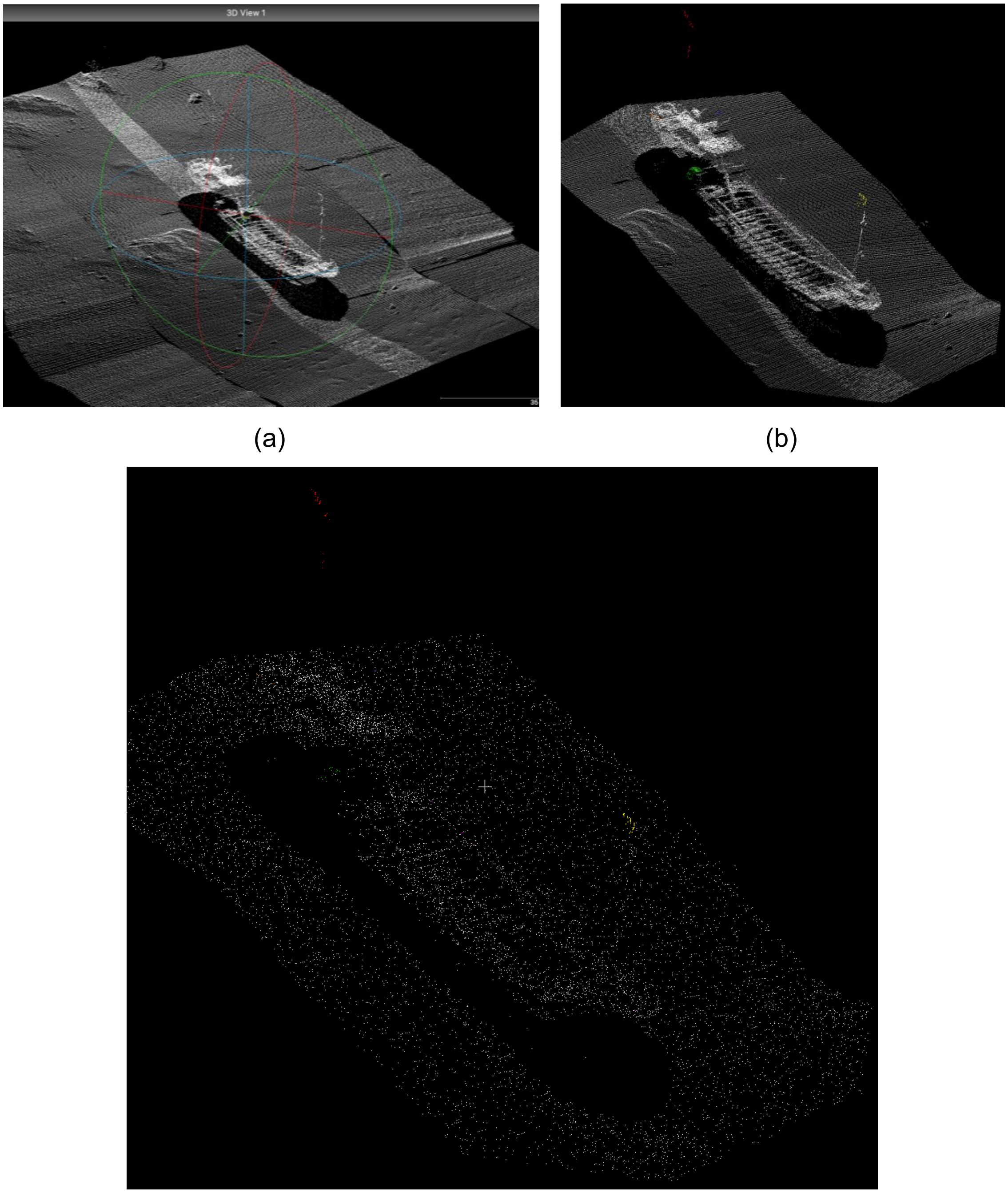
In both models, six groups of points were selected, with each group assigned one of the following colors: blue, red, yellow, green, orange, and magenta. These colors were chosen for their optimal contrast against a black background. The criteria for selecting the points were as follows:

a) One group of points represented spurious data incorrectly acquired by the acquisition system or data typically filtered or excluded during processing. This group was used to test the participant's ability to identify whether the data was accurate.
b) In both models, two vertically adjacent groups of points, not necessarily part of the ship's structure, were colored red and yellow. These groups were chosen to compel participants to observe the model from a side view.
c) Lastly, three groups of points represented features of the ship's structure. These groups were selected to assess the participants' ability to perceive small features of the model.

GB Church

The G.B. Church was the Artificial Reef Society of British Columbia's (ARSBC) first project, initiated in 1989 and completed over two years. The ship was sunk in August 1991 in Princess Margaret Marine Park near Sidney on Vancouver Island. Preparation involved stripping the vessel down to the steel, creating diver access points, and removing hazardous materials to ensure diver safety. The sinking site, chosen for its flat sandy bottom and proximity to dive shops, met all coast guard and navigation requirements. The G.B. Church quickly became a habitat for marine life like octopus and wolf eels, demonstrating the positive impact of artificial reefs on ecosystems and reducing diver traffic on natural and historical sites (Artificial Reef Society of British Columbia, 2024).

In this model (Figure 7), the red and yellow groups of points represented data that were not considered spurious but were not part of the ship's structure. The magenta group of points represented spurious data. The blue, green, and orange groups represented features of the ship's structure.



(a) (b)

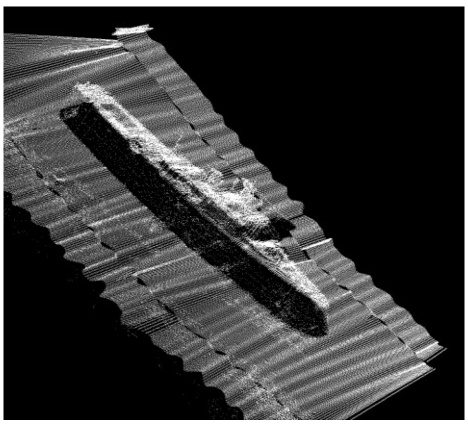
(c)

Figure 7 **(a) GB Church Point Cloud Raw; (b) GB Church Point Cloud Color; and (c) GB Church Point Cloud Sample**

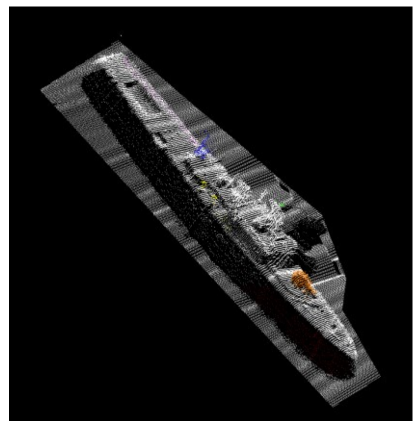
HMCS Mackenzie

The lead ship of her class, HMCS Mackenzie, was built by Canadian Vickers Limited in Montreal and commissioned on 6 October 1962. Over 23 years, Mackenzie operated in the Pacific with the Second Canadian Destroyer Squadron and Training Group Pacific, participating in various exercises. After 30 years of service, she was decommissioned on 3 August 1993 and sold to the Artificial Reef Society of BC. She was scuttled near Rum Island on 16 September 1995 (Artificial Reef Society of British Columbia, 2024).

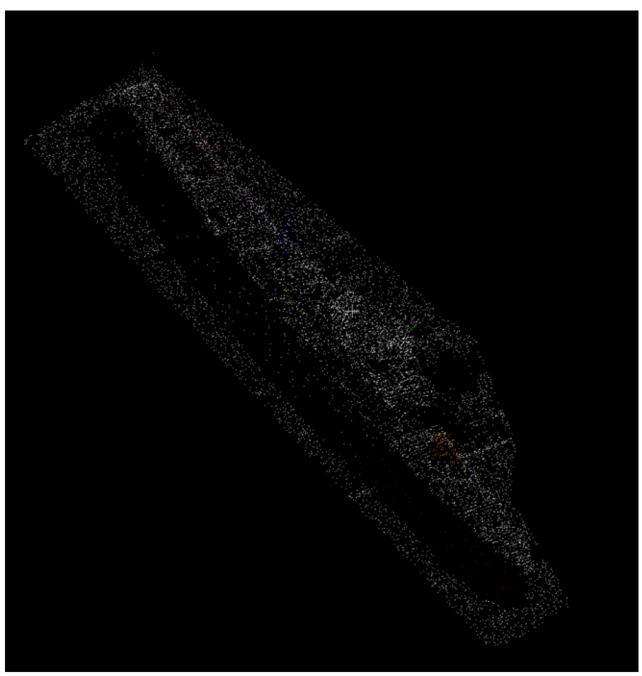
In this model (Figure 8), the orange group of points represented spurious data. All the other groups represented features of the ship's structure.



(a)



(b)



(c)

Figure 8 (a) HMCS Mackenzie Point Cloud Raw; (b) HMCS Mackenzie Point Cloud Color; and (c) HMCS Mackenzie Point Cloud Sample

3.3.3. Display Interface Technologies Used

Two interfaces, Interface DT and Interface AR, were used to view and manipulate the 3D models (Figure 9).

The desktop interface (“Interface DT”) consisted of a flat-screen monitor and a mouse resting on a table while the individual remained seated in a chair. The mouse, containing three buttons, allowed the individual to rotate, translate, and zoom in and out on the model.

The AR interface (“Interface AR”) consisted of a mobile device (smartphone) capable of projecting the 3D model in AR on a table (the same one used in the DT interface). At the same time, the individual remained standing and could move around the table freely. The touch-sensitive screen allowed the individual to rotate, translate, and increase and decrease the model's size (Figure 10). It is observed that because the 3D model was anchored to the table's surface, there was a limitation on the rotation of the model on the axes parallel to the table’s plane.

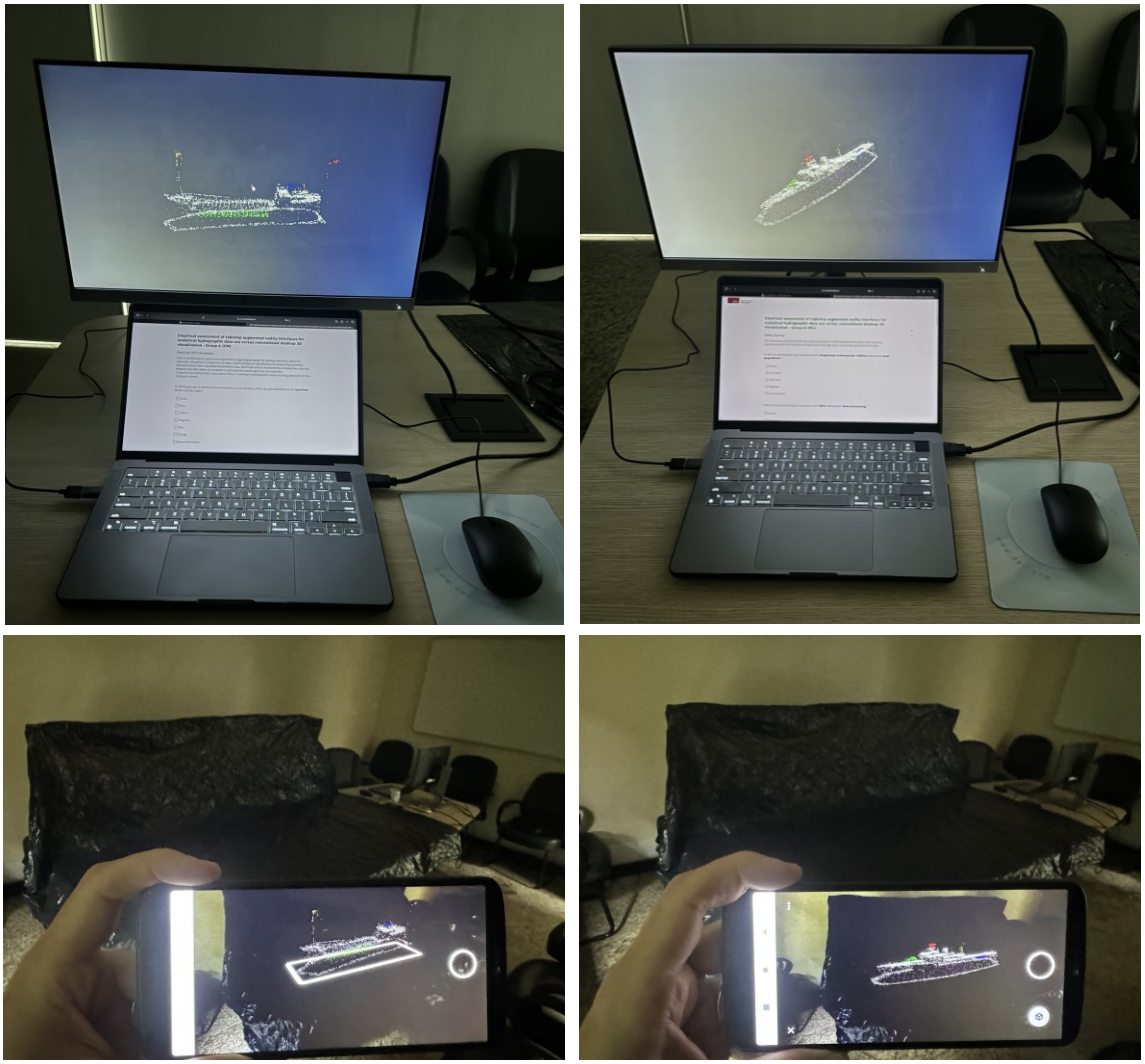
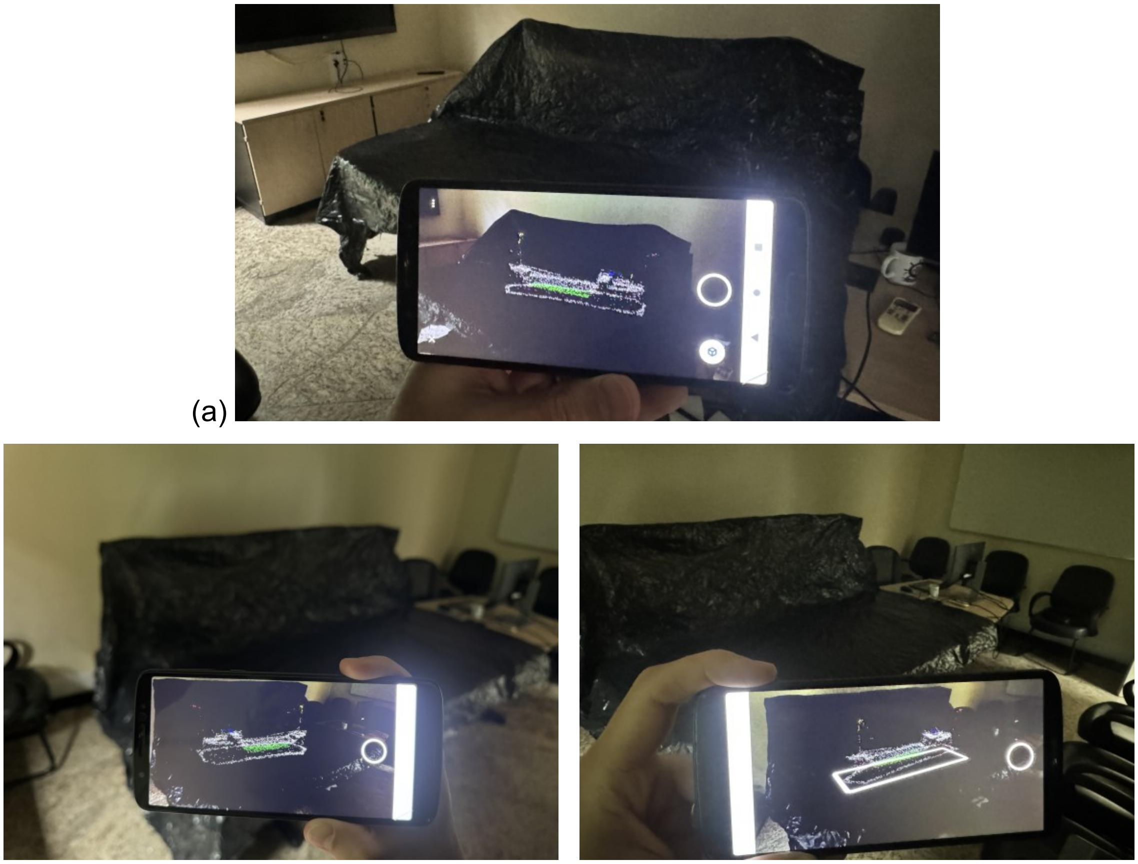


Figure 9 **DT Interface GB Church model (top left), DT Interface HMCS Mackenzie (top right), AR Interface GB Church model (bottom left), AR Interface HMCS Mackenzie (bottom right).**



(a) (b) (c)

Figure 10 The 3D AR bathymetric data visualization, seen registered to a desk covered in a blackout sheet, viewed through a handheld mobile device in the hydrographic office configured to conduct this study.

3.3.4. Participants

Participation in this study was entirely voluntary. Participants could choose not to participate without any impact on their employment, partnerships, or services they currently receive.

The participants were 42 volunteer hydrographer analysts and Cartographic Engineers from the Brazilian Navy Hydrographic Office in Rio de Janeiro, Brazil. Data collection took place in May and June 2024. Participants were recruited via personal contact and were questioned about their experience with 3D visualization and bathymetric data before testing. While all participants had some prior experience with 3D visualization applications, not all had experience with the specific 3D geographical data used in this study. None were familiar with the presented bathymetry models.

The sample was deliberately chosen to explore the performance of experienced users with hydrographic expertise, focusing on perception, identification, and classification tasks. The participants represented nearly all analysts from the BN Hydrographic Office. To balance the order of interface use, participants were divided into two groups (A and B), ensuring an equal number of participants for each interface. All subjects had normal or corrected vision and no motor or movement restrictions.

Both groups had identical experimental conditions, including lighting, temperature, and other environmental factors. Participants consented to the experimental procedure and participated voluntarily, with the option to withdraw at any time. They were instructed to perform tasks with maximum attention and told that precision in answering was more important than speed, though their completion time to answer each question in each task phase would still be recorded.

Due to the anonymous nature of the survey, participants could not withdraw their responses once submitted.

3.3.5. Background and Operational Survey

The voluntary participants were invited to self-assess themselves by answering an initial questionnaire about their previous experiences with 3D interfaces and general knowledge about manipulating bathymetric data. The answers were graded in five degrees: expert, advanced, mid-level, beginner, and no experience. There were 11 questions:

- How do you evaluate your experience with Single beam Echosounder (SBES) bathymetric data acquisition?
- How do you evaluate your experience with SBES bathymetric data processing?
- How do you evaluate your experience with Multibeam Echosounder (MBES) bathymetric data acquisition?
- How do you evaluate your experience with MBES bathymetric data processing?
- How do you evaluate your experience with bathymetric data feature classification?
- How do you evaluate your experience with desktop 3D data visualization?
- How do you evaluate your experience with Augmented Reality (AR) 3D data visualization?

- How do you evaluate your experience with Virtual Reality (VR) data visualization?
- How do you evaluate your experience with 2D computer or console games?
- How do you evaluate your experience with 3D computer or console games?
- How do you evaluate your experience with AR games?

3.3.6. Normalization Phase

The normalization phases were placed at the beginning of each interface task battery so that the participants could familiarize themselves with the testing design and control devices and flatten out the possible differences in skills in handling both desktop and AR devices between the participants. The training task required the participants to explore a generic bathymetric dataset with marks randomly placed. The participants were instructed about controlling their actions with the mouse and keyboard (desktop interface) and the AR device and then asked to practice control of a training map for 3 minutes.

3.3.7. Task and Stimuli

The experiment was divided into two phases. The first used the desktop computer interface, the standard interface for bathymetric data visualization, and the second used mobile devices to emulate the augmented reality effect. All participants were submitted to tasks in both interfaces, with one battery in each interface. To balance the experiment, the participants were divided into two sub groups. Each subgroup performed the tasks in both interfaces but alternating the order. In this way, a subgroup first performed the tasks in the Desktop interface, second in the AR interface, and the other subgroup in the reverse order.

Tasks and scores

The tasks assigned to the participants comprised the following:

a) Of the groups of colored points indicated, which do you consider spurious (select all that apply)?
b) Of the groups of colored points indicated, which do you consider part of the sunken ship (select all that apply)?

c) Which of the groups of colored points indicated is closest to the sea surface (shallowest depth), regardless of whether the data is spurious?
d) How many crane booms can you identify on the ship?
e) How many masts can you identify on the ship?
f) How would you classify the type of shipwreck?

For the first two tasks, each group of colored points was individually evaluated, resulting in a score ranging from 0 to 6. A score of 0 indicated that all groups were incorrectly evaluated, whereas a score of 6 indicated that each group was correctly assessed. Points were awarded solely for the correct answers for the remaining four tasks.

Response Confidence

Following each task's completion, participants were asked to rate their confidence in their responses on a seven-point scale, where one indicated "Not confident at all" and 7 indicated "Extremely confident."

It was decided to incorporate confidence assessments to help gain deeper insights and improve the overall validity and reliability of the study. Asking about an individual's confidence level was important, for instance, to correlate confidence with accuracy, identify potential biases, and enhance the predictive of research findings.

3.3.8. Post Survey

Upon completing all tasks, volunteers were invited to answer a post-experiment questionnaire regarding their experiences. The questions included:

a) Rate your ease of perceiving the horizontal position of the selected points in raw MBES data using AR / DT data visualization interfaces.
b) Rate your ease of perceiving the vertical position (depth) of the selected points in raw MBES data using AR / DT data visualization interfaces.
c) Rate your ease of identifying whether the selected points are considered spurious data in raw MBES data using AR / DT data visualization interfaces.
d) Rate your ease of identifying whether the selected points belong to the structure of the sunken ship in raw MBES data using AR / DT data visualization interfaces.

3.3.9. Exit Survey

After completing both stages of the experiment (desktop and AR environment), volunteers responded to a final reflective questionnaire with comparison questions between the stages performed. For the first four questions, participants indicated whether one of the two interfaces was better or whether there was no difference. The questions included:

a) Did either of the two interfaces (desktop or AR) provide a clearer understanding of the spatial horizontal positioning of the groups of colored points in each task?
b) Did either of the two interfaces (desktop or AR) provide a clearer understanding of the spatial vertical positioning (depth) of the groups of colored points in each task?
c) Did either of the two interfaces (desktop or AR) make identifying parts of ships, such as masts and crane booms, easier?
d) Did either of the two interfaces (desktop or AR) support a more straightforward inspection (exploration) of the dataset?
e) Do you think the AR bathymetric data visualization prototype you just used would be useful in the everyday hydrographic office workflow?
f) In your opinion, which affordances of the AR interfaces do you perceive to support hydrographic office data operations best?
g) In your opinion, which characteristics of AR-based data visualization do you perceive to undermine hydrographic data visualization or present challenges that need to be overcome?
h) Is there any other feedback you would like to share about these DT/AR interfaces in your workflow?

3.4. Results

3.4.1. DT Interface vs. AR Interface: Background and Operational Survey

Hydrographic experience

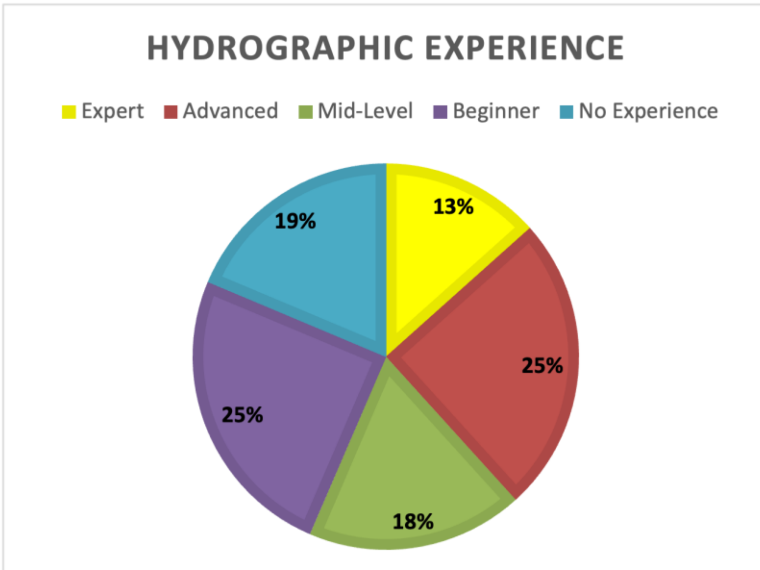


Figure 11 Hydrographic Experience results graph

The pie chart titled "Hydrography Experience" represents the distribution of responses to five questions about different aspects of hydrography experience:

a) How do you evaluate your experience with Single Beam Echosounder (SBES) bathymetric data acquisition?
b) How do you evaluate your experience with SBES bathymetric data processing?
c) How do you evaluate your experience with Multibeam Echosounder (MBES) bathymetric data acquisition?
d) How do you evaluate your experience with MBES bathymetric data processing?
e) How do you evaluate your experience with bathymetric data feature classification?

From this data, the most common experience levels are "Advanced" and "Beginner," which account for 25% of the respondents. "No Experience" is also significant, accounting for 19% of the respondents. Mid-Level experience is held by 18% of the respondents. The "Expert" level is the least common, with 13% of respondents rating themselves as such.

This distribution indicates a diverse range of expertise among the respondents, with a notable portion having significant experience (Expert and Advanced combined account for 38%) and another considerable portion with minimal to no experience (No Experience and Beginner combined account for 44%).

Desktop Interface experience

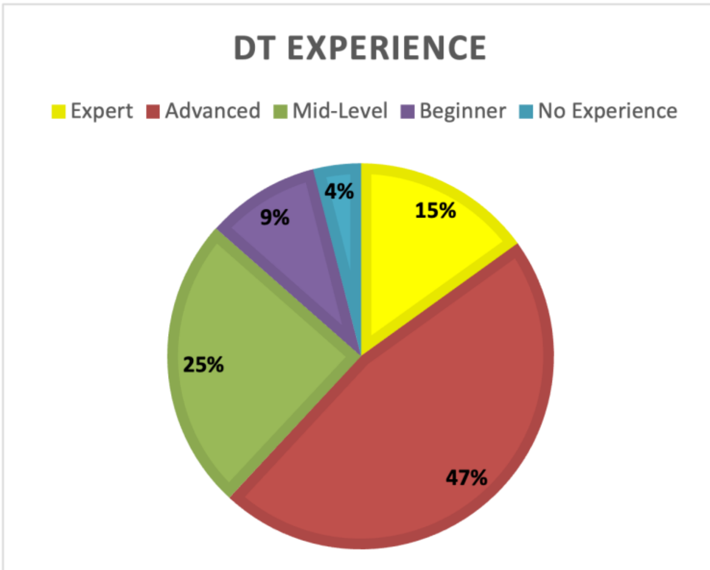


Figure 12 Desktop Interface Experience results graph

The pie chart titled "Desktop Interface Experience" represents the distribution of responses to three questions about experience with desktop interfaces:

a) How do you evaluate your experience with desktop 3D data visualization?
b) How do you evaluate your experience with 2D computer or console games?
c) How do you evaluate your experience with 3D computer or console games?

This data shows that the most common experience level is "Advanced," making up 47% of the respondents. Mid-Level experience is also significant, accounting for 25% of the respondents. The "Expert" level is held by 15% of the respondents. The "Beginner" level is relatively low, with 9% of respondents rating themselves as such. "No Experience" is the least common, with only 4% of respondents. This distribution indicates that most respondents have significant experience with desktop interfaces (Advanced and Expert combined account for 62%). A smaller portion has minimal to no experience (Beginner and No Experience combined account for 13%).

AR Interface experience

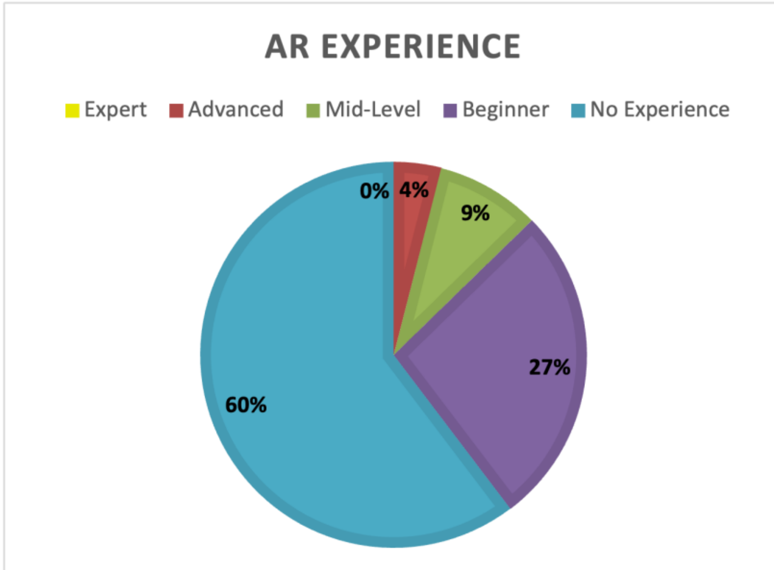


Figure 13 Augmented Reality Experience results graph

The pie chart titled "Desktop Interface Experience" represents the distribution of responses to three questions about experience with augmented and virtual reality interfaces:

a) How do you evaluate your experience with Augmented Reality (AR) 3D data visualization?
b) How do you evaluate your experience with Virtual Reality (VR) data visualization?
c) How do you evaluate your experience with AR games?

From this data, it can be observed that most respondents have no experience, accounting for 60%. A significant portion of respondents are beginners, accounting for 27%. Only 9% of respondents have a mid-level experience. There are no respondents with advanced or expert-level experience. This distribution indicates that most respondents have little to no experience with augmented reality (AR) and virtual reality (VR) interfaces (No Experience and Beginner combined account for 87%). Only a tiny fraction have mid-level experience, and no respondents have advanced or expert experience.

3.4.2. DT Interface vs. AR Interface: Task Score

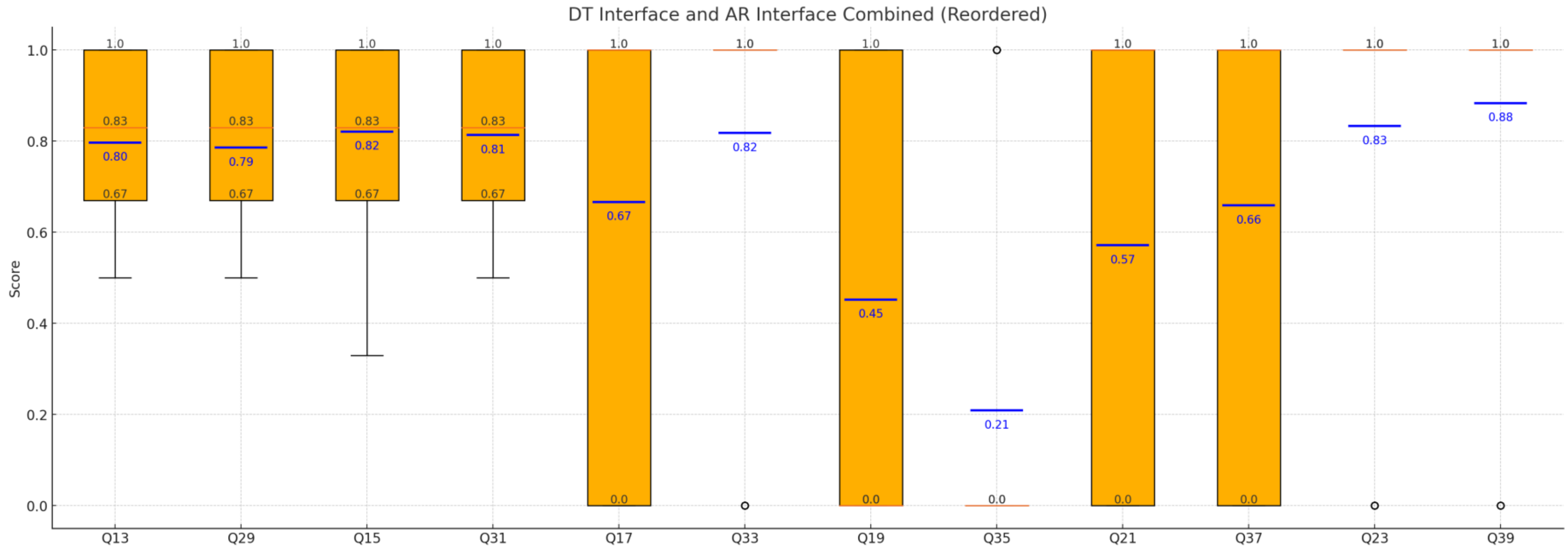


Figure 14 Desktop and Augmented Reality Interfaces score

Description of the Color Code in the Graphs

The box and whisker plots presented utilize a specific color code to represent different elements of the data:

1. Orange Boxes: Represent the interquartile range (IQR) of the data, which is the range between the first and third quartiles. The box itself shows where the central 50% of the data points lie.

2. Red Horizontal Lines Inside the Box: Represents the median value of the data set. This line divides the box into two parts, indicating that half of the data points are above this value and half are below.

3. Black Whiskers: These lines extend from the edges of the box to the minimum and maximum values within 1.5 times the IQR from the quartiles. They indicate the spread of the data outside the interquartile range.

4. Blue Horizontal Lines: Represent the average (mean) values of the data sets. These lines provide an additional measure of central tendency, helping to compare the mean values across different questions.

5. Grid Lines: The grid lines in the background help to visually align the data points for easier comparison across different questions.

This color code allows for clear and detailed visualization of the statistical properties of the data, making it easier to identify central tendencies, variability, and the overall distribution of response times for both DT and AR interface questions.

Comparing questions 13 (Q13 – DT Interface) and 29 (Q29 – AR Interface) – Of the groups of colored points indicated, which do you consider spurious (select all that apply)?

The data for Q13 is centered around a high score, with most values ranging between 0.67 and 1.00. Similarly, the distribution of Q29 data closely mirrors that of Q13, with most values falling within the 0.67 to 1.00 range. Both Q13 and Q29 have an identical median value of 0.83, indicating the same central tendency for both datasets. The first and third quartiles for Q13 and Q29 are identical, demonstrating similar dispersion and range within the middle 50% of the data. The average score for Q13 is 0.80, while Q29 has a slightly lower average of 0.79, suggesting a similar overall performance across both datasets. Both datasets exhibit a consistent range from 0.67 to 1.00 and lack any outliers, indicating stable scoring patterns without extreme variations.

The data for Q13 and Q29 are remarkably similar regarding central tendency, dispersion, and overall distribution. Both questions yield high scores concentrated around the same values, suggesting that respondents perceive the aspects consistently measured by Q13 and Q29. This similarity underscores the reliability and uniformity in responses to these questions.

The Neyman Confidence Intervals for Q13 and Q29 are similar, with Q29 having a slightly higher and more precise mean estimate. Both intervals overlap significantly, suggesting that the central tendencies of these datasets are very close to each other.

Comparing questions 15 (Q15 – DT Interface) and 31 (Q31 – AR Interface) – Of the groups of colored points indicated, which do you consider part of the sunken ship (select all that apply)?

The data for Q15 is concentrated around a high score, with most values ranging between 0.67 and 1.00, indicating a central tendency towards the upper end of the scoring scale. Similarly, the data for Q31 displays a comparable distribution, with scores predominantly falling within the same range and showing a central tendency towards higher values. Q15 and Q31 share an identical median value of 0.83, highlighting their similar central tendencies. The first and third quartiles for both questions are also the same, demonstrating comparable dispersion and range within the middle 50% of the data. The average score for Q15 is 0.82, while for Q31, it is slightly lower at 0.81, indicating a similar overall performance in both datasets. Both datasets exhibit the same range from 0.50 to 1.00 and lack any outliers, reflecting consistent scoring patterns without extreme variations.

The data for Q15 and Q31 are strikingly similar in central tendency, dispersion, and overall distribution. Both questions have high scores concentrated around similar values, reflecting consistent responses. This consistency suggests that the respondents perceive the aspects measured by Q15 and Q31 similarly, underscoring the reliability and uniformity of their answers.

The Neyman Confidence Intervals for Q15 and Q31 have a similar central tendency, but Q15 suggests a slightly higher mean than Q31. The CI for Q31 is narrower, suggesting a more precise estimate of the mean for Q31 compared to Q15.

Comparing questions 17 (Q17 – DT Interface) and 33 (Q33 – AR Interface) – Which of the groups of colored points indicated is closest to the sea surface (shallowest depth), regardless of whether the data is spurious?

The data for Q17 exhibits a bimodal distribution, with scores concentrated at the lowest (0.00) and highest (1.00) values, suggesting a polarized perception among respondents. In contrast, the data for Q33 is highly skewed towards the highest score, with the majority of values being 1.00 and a few low scores, indicating a strong tendency towards the upper end of the scale. The first quartile for Q17 is at 0.00, and the third quartile is at 1.00, indicating wider dispersion and a bimodal nature. Conversely, Q33 has both quartiles at 1.00, showing no dispersion and a strong skew towards the highest score. The average score for Q17 is 0.66, whereas for Q33, it is higher at 0.82, indicating a more positive overall performance.

Both datasets share the same range from 0.00 to 1.00 and lack outliers. However, their distribution patterns differ, with Q17 being bimodal and Q33 strongly skewed towards the top. This comparison highlights the varying perceptions of the aspects measured by Q17 and Q33. Q17's bimodal distribution suggests a divided perception among respondents, while Q33's skew towards the highest score indicates more uniformly positive responses.

The Neyman Confidence Interval for Q33 suggests a higher and more precise mean than Q17. The intervals indicate a significant difference in the central tendencies of these datasets, with Q33 having a higher mean and a narrower confidence interval.

Comparing questions 19 (Q19 – DT Interface) and 35 (Q35 – AR Interface) – How many crane booms can you identify on the ship?

The data for Q19 exhibits a bimodal distribution, with scores concentrated at the lowest (0.00) and highest (1.00) values, indicating polarized responses among respondents. Conversely, the data for Q35 is highly skewed towards the lowest score, with the majority of values being 0.00 and a few high scores, suggesting a strong tendency towards the lower end of the scale.

Q19 has a median of 1.00, while Q35 has a median of 0.00, reflecting a central tendency towards the highest score for Q19 and the lowest score for Q35. The first quartile for Q19 is at 0.00, and the third quartile is at 1.00, indicating wide dispersion and a bimodal nature. In contrast, Q35 has both quartiles at 0.00, showing no dispersion and a strong skew toward the lowest score. The average score for Q19 is 0.59, whereas for Q35, it is significantly lower at 0.12, indicating a more positive overall performance for Q19.

Both datasets share the same range from 0.00 to 1.00 and lack any outliers, but their distribution patterns differ significantly. Q19 displays a bimodal distribution with significant scores at both extremes, suggesting polarized responses among respondents. In contrast, Q35 shows a strong skew towards the lowest score, indicating predominantly negative responses. This comparison highlights the differing perceptions of the aspects measured by Q19 and Q35, with Q19 receiving more balanced responses and Q35 indicating a tendency towards dissatisfaction.

The Neyman Confidence Interval for Q19 suggests a higher mean compared to Q35. There is no overlap between the intervals, indicating that the central tendencies of these datasets are significantly different, with Q19 having a higher mean and a slightly wider confidence interval.

Comparing questions 21 (Q21 – DT Interface) and 37 (Q37 – AR Interface) – How many masts can you identify on the ship?

The data for Q21 exhibits a bimodal distribution, with scores concentrated at the lowest (0.00) and highest (1.00) values, indicating polarized responses among respondents. Similarly, the data for Q37 shows a bimodal distribution with scores concentrated at both extremes, suggesting a divided perception among respondents.

Q21 and Q37 have a median value of 1.00, reflecting a central tendency towards the highest score. Both questions' first and third quartiles are 0.00 and 1.00, respectively, indicating wide dispersion and a bimodal nature. The average score for Q21 is 0.61, while for Q37, it is slightly higher at 0.66, suggesting a marginally more positive overall performance. Both datasets share the same range from 0.00 to 1.00 and lack any outliers, with similar distribution patterns. This comparison highlights the consistent nature of respondent perceptions for the aspects measured by Q21 and Q37.

The Neyman Confidence Interval for Q37 suggests a higher mean compared to Q21. There is some overlap between the intervals, indicating that the central tendencies of these datasets are similar. However, Q37 has a higher mean and a slightly narrower confidence interval than Q21.

Comparing questions 23 (Q23 – DT Interface) and 39 (Q39 – AR Interface) – How would you classify the type of shipwreck?

The data for Q23 is highly skewed towards the highest score, with the majority of values being 1.00, indicating a strong tendency towards the upper end of the scale. Similarly, the data for Q39 shows a strong skew towards the highest score, with most values at 1.00, reflecting a preference for the upper end of the scale. Q23 and Q39 have a median value of 1.00, indicating a central tendency towards the highest score. The first and third quartiles for both questions are 1.00, showing no dispersion and a strong skew toward the highest score. The average score for Q23 is 0.86, while for Q39, it is higher at 0.93, suggesting a slightly more positive overall performance. Both datasets share the same range from 0.00 to 1.00 and lack any outliers, but their distribution patterns are highly skewed towards the top. This comparison highlights the uniformity in respondent perceptions for the aspects measured by Q23 and Q39.

The Neyman Confidence Interval for Q39 suggests a higher and more precise mean than Q23. There is significant overlap between the intervals, indicating that the central tendencies of these datasets are pretty similar. Nonetheless, Q39 has a slightly higher mean and a narrower confidence interval than Q23.

3.4.3. DT Interface vs. AR Interface: Time-elapsed

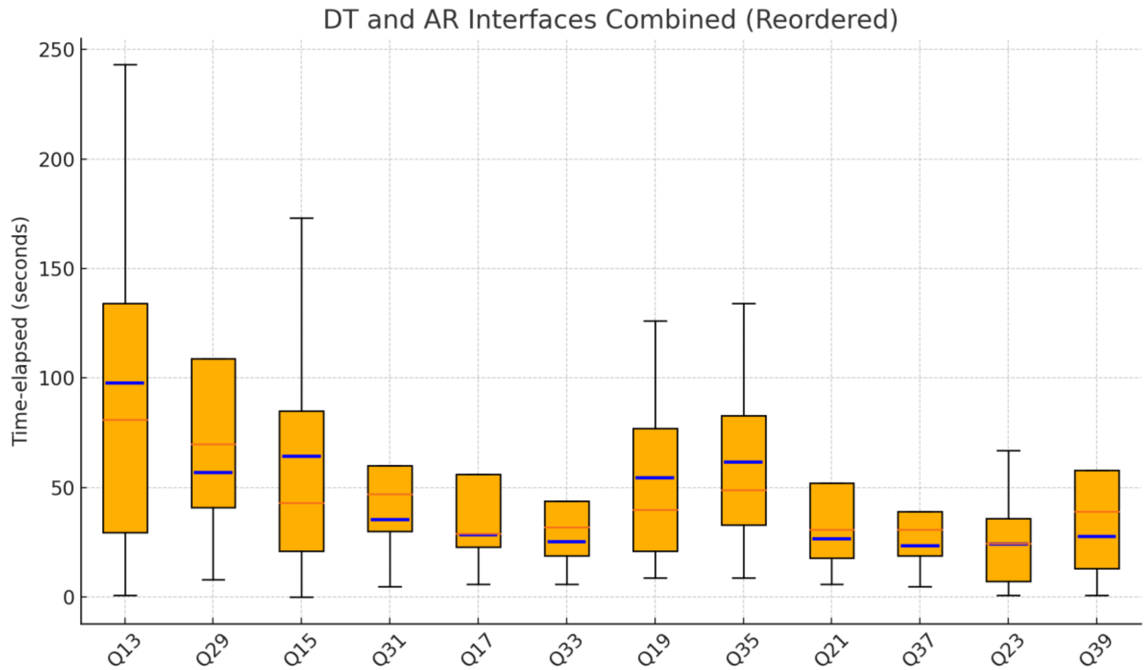


Figure 15 Desktop and Augmented Reality Interfaces time

This section presents a comparative analysis of time-elapsed statistics for two groups of questions: the DT Group (Q13, Q15, Q17, Q19, Q21, Q23) and the AR Group (Q29, Q31, Q33, Q35, Q37, Q39).

The DT Group's time-elapsed statistics reveal considerable variability across different questions. For instance, Q13 exhibits a median time of 81.0 seconds, with an interquartile range (IQR) spanning 29.5 to 134.0 seconds and an average of 90.05 seconds. In contrast, Q23, after removing outliers, shows a median of 27.5 seconds, an IQR from 8.25 to 39.25 seconds, and an average of 46.12 seconds. Other questions in this group, such as Q15 and Q17, display medians ranging from 29.0 to 43.0 seconds, with averages between 39.69 and 57.31 seconds.

The AR Group exhibits a more consistent pattern in response times. For example, Q29 shows a median time of 70.0 seconds, with an IQR from 41.0 to 109.0 seconds and an average of 92.67 seconds. Similarly, Q31 and Q35 have medians of 47.0 and 49.0 seconds, respectively, with averages around 57.62 and 59.93 seconds.

The ranges in this group, such as 8 to 317 seconds for Q29 and 1 to 259 seconds for Q39, indicate substantial variability but are generally more controlled than the DT Group.

The median time-elapsed for the DT Group tends to be higher in Q13 (81.0 seconds) and lower in other questions (27.5 to 43.0 seconds). In contrast, the AR Group exhibits a more consistent range of medians (31.0 to 70.0 seconds).

The DT Group shows broader IQRs for questions like Q13 (104.5 seconds) and Q15 (64.0 seconds), indicating greater variability. The AR Group has narrower IQRs, suggesting more consistent responses within each question.

The average time-elapsed is relatively similar between the groups. The DT Group's Q13 (90.05 seconds) and the AR Group's Q29 (92.67 seconds) have the highest averages. Other questions in both groups exhibit average times between 37.81 and 59.93 seconds.

The ranges in the DT Group are more extreme, particularly in Q13 (1 to 243 seconds) and Q23 (1 to 95 seconds without outliers). Although the AR Group also has wide ranges, such as 8 to 317 seconds for Q29 and 1 to 259 seconds for Q39, the variability is generally more controlled.

Neyman confidence intervals

Based on the provided statements and the analysis of the Neyman confidence intervals, here is a summary and critique for each comparison pair within the DT Group and AR Group:

The Neyman confidence intervals for Q13 and Q29 are similar, with both intervals overlapping substantially. This indicates that the time-elapsed data for both questions have similar central tendencies and variability, making them comparable.

Both Q15 and Q31 datasets exhibit similar means and variability, but Q15 (173) and Q31 (20) are significant outliers. Despite the similarities in distributions, the presence of these outliers highlights deviations from the central tendencies in both datasets.

The Neyman confidence intervals for Q17 and Q33 overlap, suggesting some similarity in their distributions. However, Q17 shows more variability compared to Q33.

The individual times Q17 (42) and Q33 (22) are consistent with their respective datasets, as they fall within the confidence intervals.

The overlapping confidence intervals for Q19 and Q35 indicate some similarity in their distributions. However, Q35 shows slightly more variability compared to Q19. The individual times Q19 (10) and Q35 (115) are outliers, indicating significant deviations from the central tendencies.

The confidence intervals for Q21 and Q37 also overlap, suggesting similar distributions. However, Q37 shows more variability compared to Q21. The individual times Q21 (14) and Q37 (8) are outliers, indicating significant deviations from the central tendencies.

For Q23 and Q39, the overlapping confidence intervals indicate similarity in their central tendencies. However, the Q23 dataset shows much higher variability than the Q39 dataset. The individual time Q23 (29) is consistent with its dataset, while Q39 (67) is an outlier, highlighting the difference in the presence and impact of outliers.

The comparisons consistently show that datasets within both groups (DT and AR) have overlapping confidence intervals, indicating similar central tendencies. Variability differences are noted within each comparison, highlighting how some datasets exhibit a greater spread in the data.

3.4.4. DT Interface vs. AR Interface: Response Confidence

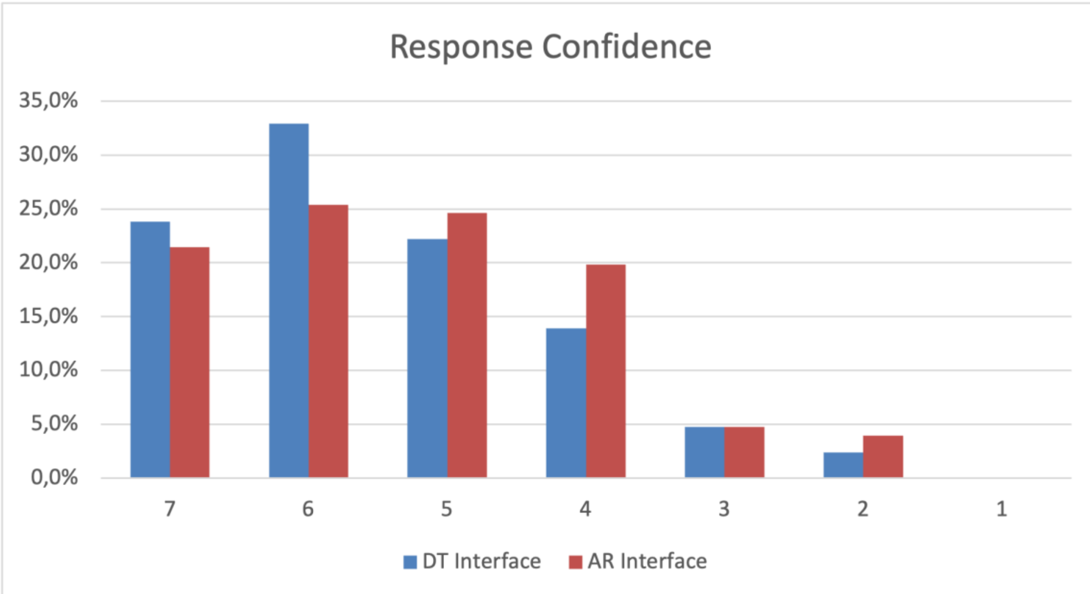


Figure 16 DT vs AR interface response confidence.

In both groups, the majority of participants reported high confidence levels. Group DT (Desktop Interface) showed higher confidence levels than Group AR (AR Interface). Conversely, Group AR reported higher medium confidence levels than Group DT. Both groups exhibited similar low confidence levels, with a slight increase in Group AR. This suggests that the Desktop interface may foster greater extreme confidence, while the AR interface tends to produce more medium confidence responses.

3.4.5. DT Interface vs. AR Interface: Post-survey

Rate your ease of perceiving the horizontal position of the selected points in raw MBES data using DT / AR data visualization interfaces

	DT Interface (Q25)	AR Interface (Q41)
Very Easy	4	1
Easy	14	18
Normal	14	12
Difficult	8	10
Very Difficult	2	1

Table 1 DT (Question 25) vs AR (Question 41) Post-Survey results

The DT interface received higher "Very Easy" ratings than the AR interface, indicating that more participants found the DT interface very easy to use. However, the "Easy" ratings favored the AR interface. Both interfaces were very close when combining "Easy" and "Very Easy" ratings, with a slight preference for AR.

The standard deviation for "Easy" and "Very Easy" ratings was higher, indicating more response variability. The average rating for "Easy" and "Very Easy" was almost identical between the DT and AR interfaces.

The "Normal" ratings were fairly close between the two interfaces, with a slight preference for DT. The "Difficult" ratings were slightly higher for the AR interface, and the "Very Difficult" ratings were very close, with a slight preference for DT. The combined "Difficult" and "Very Difficult" ratings were also close, with a slight preference for the AR interface.

Overall, participants rated the AR interface slightly higher for ease of use in the "Easy" and "Very Easy" and "Difficult" and "Very Difficult" categories. In contrast, the DT interface was preferred slightly more for "Normal" ratings.

Rate your ease of perceiving the vertical position (depth) of the selected points in raw MBES data using DT / AR data visualization interfaces.

	DT Interface (Q26)	AR Interface (Q42)
Very Easy	5	11
Easy	26	22
Normal	8	6
Difficult	3	3
Very Difficult	0	0

Table 2 DT (Question 26) vs AR (Question 42) Post-Survey results

The AR interface's "Easy" and "Very Easy" ratings are slightly higher than the DT interface's. The DT interface's "Normal" ratings are close but slightly favor the AR interface. The DT interface's "Difficult" and "Very Difficult" ratings are identical.

The average rating for "Easy" and "Very Easy" is nearly identical, with a slight preference for AR, while "Normal" ratings show a slight preference for DT. The "Difficult" and "Very Difficult" ratings are the same for both interfaces. The standard deviation for "Easy" and "Very Easy" is low, indicating consistent responses. "Normal" ratings also show low variability, and "Difficult" and "Very Difficult" ratings have no variability since they are identical for both interfaces.

Overall, participants rated the AR interface slightly higher for ease of use in the "Easy" and "Very Easy" category. In contrast, the DT interface was somewhat preferred for "Normal" ratings, with no difference in the "Difficult" and "Very Difficult" category.

Rate your ease of identifying whether the selected points are considered spurious data in raw MBES data using AR / DT data visualization interfaces.

	DT Interface (Q27)	AR Interface (Q43)
Very Easy	0	2
Easy	12	13
Normal	20	16
Difficult	6	9
Very Difficult	4	2

Table 3 DT (Question 27) vs AR (Question 43) Post-Survey results

The AR interface's "Easy" and "Very Easy" ratings are slightly higher than those of the DT interface, while the DT interface's "Normal" ratings are higher than those of the AR interface. Similarly, the AR interface's "Difficult" and "Very Difficult" ratings are slightly higher than the DT interface's.

The average rating for "Easy" and "Very Easy" is higher for the AR interface, the "Normal" rating is higher for the DT interface, and the "Difficult" and "Very Difficult" ratings are higher for the AR interface. The standard deviation for "Easy" and "Very Easy" is relatively low, indicating consistent responses, while the "Normal" rating shows more variability. The "Difficult" and "Very Difficult" ratings have low variability.

Overall, participants rated the AR interface slightly higher for ease of use in the "Easy" and "Very Easy" and "Difficult" and "Very Difficult" categories. In contrast, the DT interface was preferred for "Normal" ratings.

Rate your ease of identifying whether the selected points belong to the structure of the sunken ship in raw MBES data using AR / DT data visualization interfaces.

	DT Interface (Q28)	AR Interface (Q44)
Very Easy	1	4
Easy	14	15
Normal	23	14
Difficult	2	6
Very Difficult	2	3

Table 4 DT (Question 28) vs AR (Question 44) Post-Survey results

The AR interface has higher "Easy” and “Very Easy" ratings than the DT interface, while the DT interface has higher "Normal" ratings. The AR interface has higher "Difficult” and “Very Difficult" ratings.

The average rating for "Easy” and “Very Easy" is higher for the AR interface, the "Normal" rating is higher for the DT interface, and the "Difficult” and “Very Difficult" ratings are higher for the AR interface. The standard deviation for "Easy” and “Very Easy" is relatively low, indicating consistent responses, while the "Normal" rating shows more variability. The "Difficult” and “Very Difficult" ratings also have more variability, indicating a more comprehensive range of responses.

Overall, participants rated the AR interface higher for ease of use in the "Easy” and “Very Easy" and "Difficult” and “Very Difficult" categories. In contrast, the DT interface was preferred for "Normal" ratings.

Based on post-survey results, most participants rated tasks in the AR interface as either "Easy” and “Very Easy" or "Difficult” and “Very Difficult." In contrast, tasks in the DT interface were predominantly rated as "Normal."

3.4.6. Exit survey

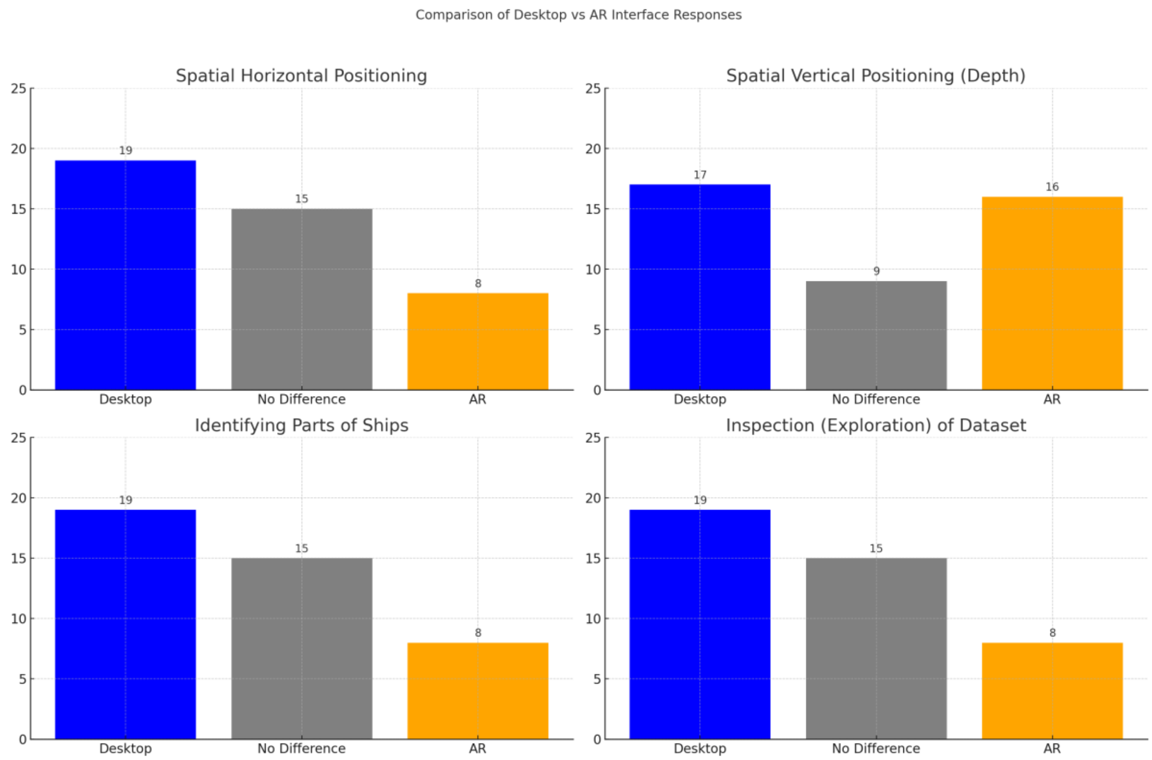


Figure 17 Exit Survey results graph

Based on exit-survey results, most participants preferred the desktop interface for spatial horizontal positioning, identifying parts of ships, and inspecting (exploring) the dataset, with fewer finding no difference and the least preferring the AR interface. However, for spatial vertical positioning (depth), preferences were similar between the desktop and AR interfaces, with a slight majority favoring the desktop.

AR bathymetric data visualization prototype usefulness

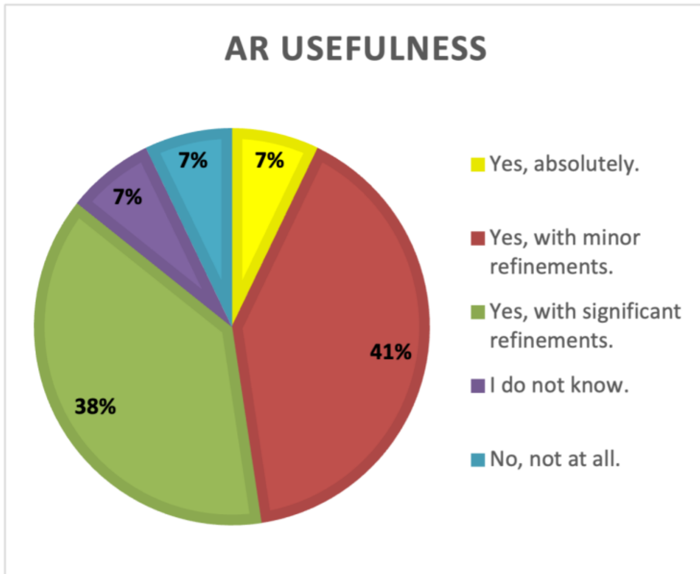


Figure 18 AR Usefulness results graph

The results of the question asking the participants' opinion about the usefulness of the AR bathymetric data visualization prototype used in the experiment in everyday hydrographic office workflow show that a significant majority (90%) believe the prototype would be useful. However, 82.5% think it requires refinements. Only a few (7.5%) are unsure about the prototype's usefulness. Another small portion (7.5%) believes the prototype is useless.

Open-ended question: In your opinion, which affordances of the AR interfaces do you perceive to best support the hydrographic office's data operations?

By the answers to the question, the volunteers indicate that, in their opinion, the affordances of AR interfaces that best support the hydrographic office's data operations include the practicality of viewing data anywhere without needing to be at the collection site and the ease of sharing data instantly by uploading it to the cloud. AR provides a better definition of data discrimination, especially in vertical viewing, and offers freedom of action with familiar image manipulation for mobile users. It enhances simulation and training, improves visualization, and provides contextual information, making distinguishing and understanding features easier. The ability to manipulate the 3D model and the improved top view of the model are also notable benefits. AR supports spatial interaction and user mobility, allowing for better viewing angles and different locations outside the office. It facilitates group visualization and interaction, serves as an alternative tool for visualization and display of results, and enhances collaborative experiences—the anchoring on the surface aids in understanding vertical points and terrain behavior. AR interfaces offer greater mobility, making them useful anywhere, and can motivate data analysis by transforming tasks into interactive experiences and overlaying contextual information onto the user's environment.

Open-ended question: In your opinion, which characteristics of AR-based data visualization do you perceive to undermine hydrographic data visualization or to be challenges that need to be overcome?

By the answers to the question, the volunteers indicate that, in their opinion, the challenges and characteristics of AR-based data visualization that may undermine hydrographic data visualization include the need for a specific environment with proper lighting to ensure clear viewing and the impact of ambient brightness and reflections. Users highlighted issues with the size and resolution of the points in point clouds and the limited ability to zoom in on parts of the object. Screen size is challenging, especially when mobile devices have low color contrast and reduced zoom capacity. Accessibility and maneuverability of devices and the longer time required to analyze data were also noted as concerns. The need for user training, familiarization with AR devices, and the infrastructure costs for acquiring and maintaining the technology were identified as significant barriers. Additionally, the dependency on a reference surface, the necessity to maintain environmental control, and the higher reliability and ease of data manipulation in desktop interfaces compared to AR were mentioned. Overall, the need for a specific physical space and environment, high costs, and adequate contrast and lighting are significant challenges that must be addressed to improve AR-based hydrographic data visualization.

Open-ended question: Is any other feedback would you like to share about these DT / AR interfaces in your workflow?

By the answers to the question, the volunteers indicate that, in their opinion, feedback on the DT/AR interfaces includes the need for options to change vertical exaggeration and axis presentation to identify the grid. While AR might not be practical for large volumes of work, it could benefit specific visualizations at data collection sites, mainly where desktop infrastructure is unavailable. Using a headset with AR devices was suggested for enhanced interaction. However, AR requires specific physical space, which may not align with the typical hydrographic office setup, making it more suitable for visualizing particular cases rather than everyday data analysis. There were calls for functionality to vary the size of cloud points, change scale, adjust color bands, and use larger screens or headsets for better visualization. AR's 3D viewing capability made data interpretation more straightforward, and its potential for training and education was highlighted. It was also suggested that the tool be expanded to VR. Although the DT interface was favored for broad model viewing due to its higher resolution and dark background, AR was preferred for detailed viewing of small features. While adjustments are needed to make AR viable for hydrographic environments, it could significantly impact bathymetric data analysis and other hydrographic services.

3.5. Discussion

3.5.1. Background Experience

Based on the distribution of experience levels in desktop interfaces, most volunteers participating in the experiment will likely possess significant proficiency and familiarity with desktop interfaces. Specifically, with 62% of respondents identifying as either "Advanced" or "Expert," it was reasonable to expect a high baseline level of performance and understanding of complex data visualization tasks among the volunteers. Likewise, low performance was expected when using the AR interface since most volunteers had little or no experience.

3.5.2. Tasks score

Due to the results of the scores, both the Desktop and Augmented Reality interfaces are perceived positively for visualizing and analyzing 3D Bathymetric data models, with high central tendencies towards the upper end of the scoring scale. The data collected in the background survey initially suggested that volunteers would have a high baseline level of performance and understanding of complex data visualization tasks. It was also expected that their performance would be lower when using the AR interface, given that most volunteers had little or no prior experience with it. However, the results partially contradicted these expectations, as the performances turned out to be similar across both conditions.

The AR interface, in particular, shows slightly higher average scores and less dispersion in several questions (Q29, Q31, Q33, Q37 and Q39), suggesting a marginally better overall performance when they need to perceive the horizontal or vertical position of the points, whether they are spurious data or not, including whether they are part of the ship's structure. Together, these findings suggest that while both DT and AR interfaces are effective, the AR interface may offer a more consistent and enhanced user experience for specific tasks such as perceiving the spatial positioning of points, identifying spurious data, and distinguishing elements of the ship's structure.

3.5.3. Tasks time-elapsed

In the analyses of time elapsed during tasks, the DT Group demonstrated higher variability and more extreme values in response times, particularly for questions like Q13 and Q15, questions that ask the volunteer to consider whether the colored points are spurious or part of the sunken ship. By contrast, the AR Group exhibits more consistent and narrower distributions, suggesting a more uniform user experience with AR interfaces. Again, contrary to what one might expect from performance, in terms of speed, both interfaces presented comparable duration times. The greater experience with the DT interface on the part of the volunteers did not translate into a shorter analysis time, just as the lesser experience with the AR interface did not translate into a more extended analysis time either.

The analysis uses Neyman confidence intervals to compare datasets within and between the DT and AR groups, highlighting distribution similarities and identifying significant outliers.

3.5.4. Post-survey and Exit-survey

The desktop (DT) interface was generally preferred for spatial tasks, particularly horizontal positioning, identifying parts of ships, and dataset exploration. This preference indicates that participants found the desktop interface more reliable and manageable for these specific tasks, probably due to familiarity, or convention. However, the preference was well-balanced when considering vertical positioning.

The AR interface received polarized responses about the overall task difficulty ratings, with participants rating tasks as either "Easy” and “Very Easy" or "Difficult” and “Very Difficult." This polarization may suggest that while some participants found the AR interface highly intuitive and efficient for specific tasks, others struggled significantly. On the other hand, the DT interface received predominantly "Normal" ratings, indicating a more consistent and moderate user experience.

Some possible explanations for why participants might rate AR and DT interfaces differently regarding ease of use, might include immersion, familiarity, learning curve, cognitive load, and user preferences.

Unpacking the potential benefits of AR and being mindful of subtleties

AR provides a more immersive and interactive experience, which could make perceiving points more straightforward and intuitive [42]. One of the most powerful characteristics of AR is its ability to bring digital 3D objects, such as bathymetric data visualizations, into everyday spaces and robustly anchor them to physical surfaces using tracking, registration, and rendering. This spatial integration means that 3D data is no longer confined to a 2D display interface but can be seamlessly combined with the real-world workspace, particularly the hydrographic desk workspace. This integration leverages the importance of proprioceptive cues, which have been demonstrated to enhance geographic learning in the earliest examples of AR (Singh and Ahmad, 2024).

The significance of AR lies in its ability to combine virtual and real 3D spaces, providing perceptual benefits for users. By experiencing digital content within a real-world proprioceptive context, users of robust AR visualization systems can achieve higher "Easy” and “Very Easy" ratings, reflecting their opinions and reinforcing the intuitive nature of AR. This integration not only enhances productivity and data interpretation but also creates more interactive and immersive work experiences (Shelton and Hedley, 2002, 2004).

It is also worth commenting on the fact that AR visualization experiences can take several forms, and be achieved using a variety of spatial computing-enabled display devices. In this particular case, we used simple natural feature tracking via the Sketchfab application, which is made accessible by the use of a hand-held Android mobile device (smartphone). Using such a configuration allows the user to use a phone (or, for that matter, a tablet) function as a 'lens' through which the user may view the real world, 'augmented' with virtual content (in this case, the point clouds of the GB Church and HMCS MacKenzie). An alternative to this approach would be to use an AR-enabled head-mounted display. Such as a Meta Quest 3 with pass-through MR or pass-through augmented reality (AR). While the 3D virtual content (point cloud visualization) would stay the same, the user's experience of it would be through the headset attached to their head. And, because the headset optically fills the user's field of view (typically using a gasket around the 'goggles'), the user's only field of view is augmented. This contrasts an 'AR lens' metaphor using smartphones and tablets - where the user can see both AR views through the device, at the same time as the unmodified view of the real world all around. The head-mounted pass-through AR or MR approach may feel more elegant and integrated (and hands-free). At the same time, the AR lens approach may be more cost-effective and deployable by using everyday phones and tablets owned by users. The hand-held nature of the AR lens mode may also reinforce the proprioceptive function of the user experience by providing additional skeleto-muscular force-feedback that further calibrates the user's spatial perception of visualizations based on vision and vestibular feedback. Quantifying the potential impact of different AR interface configurations on spatial perception and interpretation of the bathymetric datasets would be an interesting project to build upon the current work.

Familiarity with DT Interfaces

Background results showed that participants are more accustomed to DT interfaces for standard or routine tasks, which could explain their preference to rate the tasks as "Normal." In other words, the familiarity and traditional use of DT interfaces might make them more comfortable with regular or less challenging tasks. On the other hand, background results showed that participants are less accustomed to AR, which could result in difficulties while handling the mobile device, resulting in higher ratings in the "Difficult" and "Very Difficult" category. This raises an interesting question for future work: Would the performance differ if participants had equal previous experience?

Learning Curve and Adaptability

The AR interface might have a steeper initial learning curve but offers superior ease of use once participants become accustomed to it, leading to higher ratings in the "Easy" and "Very Easy" categories. Participants also highlighted this issue that needs to be overcome to properly implement the interface in the routine activities of a hydrographic office.

The more familiar DT interface might have a lower learning curve but lacks AR's advanced visualization capabilities, making it preferred for everyday tasks but less effective for both “Difficult” and “Very Difficult” tasks.

Visual and cognitive load

AR interfaces can reduce cognitive load by providing a more natural and intuitive visualization, making it easier to grasp simple and complex spatial relationships (Keller, Rumann and Habig, 2021; Teng *et al.*, 2023). This could explain higher ratings for both “Very Easy” and “Very Difficult” tasks. For tasks that are not too simple or too complex (i.e., everyday tasks), the DT interface might be seen as more efficient and straightforward, resulting in higher “Normal” ratings.

User Preferences and Biases

The novelty and innovative appeal of AR might bias participants to rate it higher for ease of use in both simple and complex scenarios. Conversely, some participants might be biased towards traditional DT task interfaces due to long-term usage and comfort.

Open-ended questions

The volunteers provided largely coherent answers to the open questions. Both responses highlighted the practicality and mobility of AR in hydrographic data operations and agreed on AR's potential to enhance collaborative experiences. However, there were conflicting opinions. Some of the reasons for these differing views could be varying levels of prior experience with AR technology, differences in personal preferences for visualization methods, and the specific contexts in which individuals have used hydrographic data. Additionally, discrepancies in the perceived ease of use and the effectiveness of AR tools for particular tasks might have contributed to these differing opinions.

Different Experiences and Backgrounds and Exposure to Technology

According to the background survey results, although the volunteers are part of a selected group that includes hydrographers and Cartographic Engineers, they have, at some level, diverse professional experiences, educational backgrounds, and familiarity with 3D visualization technologies (Desktop and AR). These factors all influence their perceptions and opinions. For example, those with more AR experience were more aware of its benefits and limitations, such as the need for specific environmental conditions or high costs. For instance, in the first answer, some volunteers emphasize the ability to view and interact with data using AR interfaces in various environments. In contrast, some highlighted in the second answer the necessity for specific environments, such as the need for proper lighting and controlled environments for effective AR visualization, noting that AR's mobility and flexibility come with certain environmental constraints.

Likewise, those who have used DT interfaces extensively may have different insights than those new to it. Experienced users might appreciate the practical benefits more, while novices might focus on the challenges and learning curve (Unwin, 2020).

Specific Roles and Responsibilities and Perceived Value and Impact

As the recruitment process did not restrict the organization's rank or function for survey participants, volunteers probably included personnel from different ranks (it is impossible to be sure due to the anonymized aspect of the survey). Their specific organizational roles can shape an individual's opinions (Hewes, 2019). For instance, a data analyst might focus on AR's technical challenges, while a manager might emphasize its strategic benefits for operations.

Likewise, individuals might perceive the value and impact of AR differently based on how directly it affects their work. Those who see immediate benefits in efficiency and visualization might be more favorable, whereas those who encounter obstacles might be more critical.

Personal Preferences, Comfort Levels, Bias, and Subjectivity

Individual comfort levels with new technology can vary. Some might find AR interfaces intuitive and easy to use, while others might struggle with transitioning from traditional methods. For example, the second text suggests that desktop interfaces offer higher reliability and ease of data manipulation than AR. Also, personal biases and subjective preferences can shape how individuals perceive the advantages and disadvantages of AR technology. These biases can be based on previous experiences with similar technologies or general attitudes toward technological innovation. For example, the first answer highlighted familiar image manipulation and ease of use for mobile users. In contrast, the second answer emphasized the need for user training and familiarization with AR devices.

Users value AR differentially

People may value or prioritize aspects of AR technology differently. Some might focus on its potential for improving data visualization and collaboration, while others might concentrate on technical challenges and usability issues. For example, both answers discuss the impact of AR on data visualization and interaction. The first answer mentions AR facilitating group visualization and interaction, emphasizing AR's advantages in providing spatial interaction and contextual information. The second answer points out challenges related to screen size, resolution, and zoom capacity, which are critical to effective visualization.

In summary, while the desktop interface was preferred for specific spatial tasks due to its perceived reliability and ease of use, the AR interface elicited mixed reactions, suggesting it might offer significant benefits for some users while posing challenges for others. This could point to the AR interface's potential for high usability in optimal conditions and highlight areas where user experience can be inconsistent and needs improvement.

Using experience empirical study of hydrographic AR, to inform the design of future AR-enabled hydrographic workspaces

Finally, and with an eye to future work also, some comments on the nature of the AR workspace. The AR ‘workspace’ background for our empirical work was a conventional tabletop desk space with a black cloth draped over it. This homogenous dark background was used to make the fine points of the point cloud perceivable (see Figures 9 and 10) and so that users were focused on the characteristics of the 3D point cloud in AR (and to avoid the potential for visual dissonance between real-world background and virtual AR overlays). We intentionally started with this basic configuration (plain background) since the present study was focused on basic task performance and specialized user audience reception and feedback rather than an investigation of visual dissonance (which will be engaged in future work).

Indirectly, the current study helps to raise a number of questions and opportunities for the future design of AR workspaces. Evolving from the homogenous dark workspace backgrounds to intentionally gridded workspace backdrops may offer to strengthen the proprioceptive function and depth cues and the potential to improve judgments of orientation, position, and dimensions of structures in 3D hydrographic point clouds. To this end, we have already begun developing prototypes of these workspaces (see Figure 19)

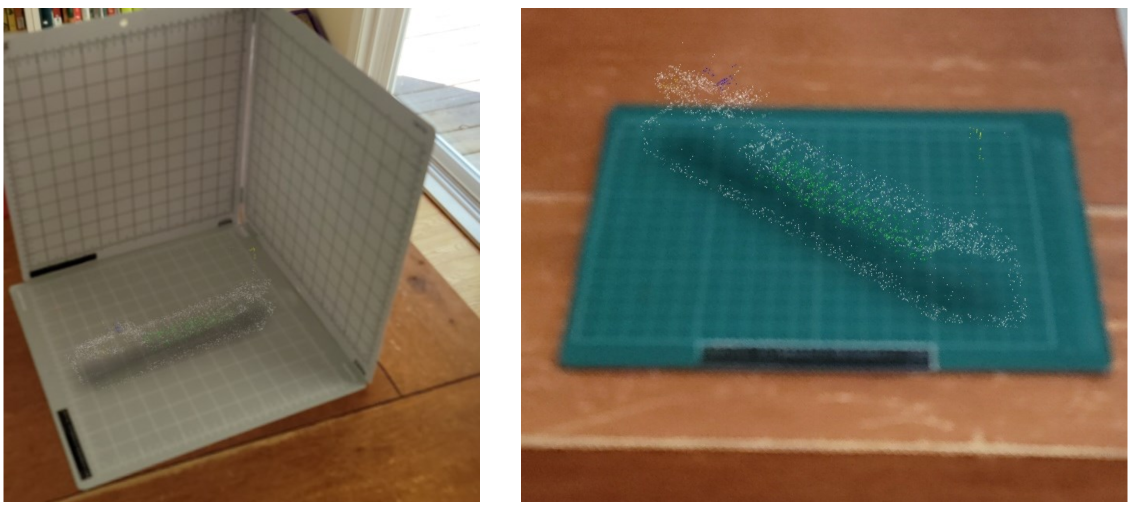


Figure 19 AR workspace prototypes

We believe a map table or workspace designed specifically for AR use, equipped with a gridded surface, could provide strong perceptual, spatial, and proprioceptive cues to support hydrographic interpretation. Future work to enhancing these aspects of the AR-enhanced hydrographic workspaces may aid users in accurately interpreting complex data, thereby improving overall performance and user satisfaction. This could lead to AR-enhanced hydrographic map tables in land-based facilities and in the command spaces of vessels. Future research will pursue this.

3.6. Conclusion

In conclusion, this study has provided new, valuable insights into the comparative effectiveness of tabletop augmented reality (AR) interfaces and conventional desktop computer monitors for hydrographic practitioners' perception and interpretation of 3D bathymetric visualizations. Through a comprehensive two-phased experiment, we assessed participants' performance across both interface types as they engaged in a series of perceptual and interpretive tasks using identical bathymetric datasets.

The findings indicate that while both interfaces support the visualization of 3D bathymetric data, the AR interface may offer advantages in terms of spatial perception and depth understanding. Participants using the AR interface demonstrated slightly improved accuracy and more uniform completion times, particularly in tasks requiring detailed spatial structure analysis and depth perception. This suggests that the ability of AR to combine 3D digital data visualizations with everyday spaces offers proprioceptively powerful user experiences that may enhance hydrographic data use and interpretation nature of AR, coupled with its ability of AR to provide an intuitive and engaging visualization environment, this may enhance the user's ability to comprehend complex 3D spatial relationships.

Despite its widespread use and familiarity among practitioners, the desktop monitor was not more effective in facilitating an in-depth understanding of 3D bathymetric structures than an AR interface. Despite the limitations of the restricted field of view inherent to small mobile devices, the AR displays allowed participants to perform satisfactorily, highlighting the interface's ability to overcome the challenges faced in accurately interpreting 3D data.

These results underscore the potential of tabletop AR interfaces as a tool for hydrographic analysis, offering a promising alternative to traditional desktop-based methods. By enabling a more natural and effective interaction with 3D visualizations, AR may enhance the analytical capabilities of hydrographic practitioners, leading to more precise and informed decision-making in maritime navigation, resource management, and environmental monitoring.

Future research should explore the integration of AR interfaces with other advanced visualization and interaction technologies and the long-term impacts of AR adoption on hydrographic practices. Further exploration of how to prepare everyday spaces to maximize the proprioceptive strengths of experiencing hydrographic data visualizations via AR, should be explored. This might lead to an ability to create standardized AR hydrographic data viewing bays like "hydrographic AR holodecks". Finally, investigating user training and the development of standardized guidelines for AR interface design could further optimize the benefits observed in this study, ensuring broader and more effective application across the hydrographic community.

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Chapter 4. Conclusions

4.1. Summary

This thesis addresses the critical issue of visualizing 3D bathymetric data for creating and updating nautical charts, which traditionally rely on 2D interfaces like computer screens. The research has investigated the potential of 3D spatial interface technologies, exceptionally mixed reality (MR), to enhance the perception, interpretation, and practical use of 3D hydrographic data sets. This involved developing data visualization prototypes and gathering empirical evidence on how these advanced interfaces impact perceptual, interpretative, and task performance outcomes.

4.1.1. Returning to the Research Questions

Three core research questions drove the study: Do conventional hydrographic data visualization platforms differ from AR platforms regarding users' perceptual outcomes? How do task performance outcomes compare between conventional and AR hydrographic data visualization platforms? Are AR interfaces suitable for integration into everyday hydrographic data analysis? To answer these questions, the research examined differences in spatial feature identification, the perception of spatial relationships in hydrographic datasets, and the accuracy and speed of task performance across both visualization platforms. Furthermore, it explored which affordances of AR interfaces users perceive as most beneficial or challenging for hydrographic data operations.

4.1.2. Returning to the Research Objectives

The research objectives included a comprehensive literature review on bathymetric data visualization, assessing current visualization approaches, and identifying ongoing trends and challenges. The study aimed to demonstrate conventional and AR interfaces' comparative capabilities and limitations in visualizing hydrographic data by developing prototypes and conducting empirical evaluations.

This thesis consisted of four chapters: an introduction, two main chapters written as stand-alone papers submitted to peer-reviewed journals, and a conclusion. These papers collectively introduced current practices within the hydrographic community, discussed emerging technological methodologies to supplement and enhance national hydrographic service production, and presented workflows developed to achieve the research objectives. Ultimately, this thesis provided valuable insights into the potential of mixed reality to revolutionize hydrographic data visualization, offering a foundation for future advancements in the field.

4.2. Research contributions

4.2.1. A review of the state of emerging tools and interfaces in hydrographic data visualization

This thesis presented several significant contributions to the field of bathymetric data visualization and interpretation through the application of emerging tools and interfaces, particularly Augmented Reality (AR). Chapter 2 provided a thorough literature review to identify and document trends in the technologies and interfaces used for hydrographic visualization. It summarized the platforms and methods currently employed to visualize bathymetric data in nautical cartographic production and discusses the potential utility and implications of emerging tools and interfaces. based on reported outcomes in the selected literature.

4.2.2. An empirical study of user ability to perceive and interpret bathymetric data visualizations using tabletop AR vs 3D visualizations on 2D screens

Building on the literature review, Chapter 3 examined hydrographic practitioners' ability to perceive the spatial structure and relationships of 3D bathymetric visualizations using tabletop augmented reality (AR) interfaces compared to conventional desktop computer monitors. A two-phased experiment was conducted, comparing the performance of two groups of participants using a tabletop AR interface and a desktop monitor to view and perform perceptual and interpretation tasks with identical visualizations of bathymetric datasets. This study explored the potential of emerging tools and interfaces to enhance bathymetric data visualization compared to traditional devices.

Framework Development for AR-based Visualization of Bathymetric Data

A framework for AR-based visualization of bathymetric data has been developed, encompassing data preprocessing, visualization techniques, and user interaction mechanisms. This framework is a model for future research and development, offering a structured approach to incorporating AR into bathymetric studies. The thesis emphasized a user-centered design approach, incorporating feedback from domain experts to refine the AR visualization tools iteratively. The evaluation of these tools through user studies demonstrated improved accuracy and efficiency in data interpretation, highlighting the practical benefits and potential for adoption in marine and environmental sciences.

Enhancements in Interpreting Multidimensional Bathymetric Data Using AR

This research used AR to provide enhanced methods for interpreting multidimensional bathymetric data. The ability to visualize data layers concurrently and interactively explore datasets in 3D could lead to a deeper understanding of complex underwater topographies and geological features. The findings and methodologies presented in this thesis contribute to the growing knowledge of advanced visualization techniques for scientific data. This research laid some groundwork for future explorations and innovations in the field by addressing the challenges and opportunities of using AR for bathymetric data.

Significance in Applied Communities of Practice

The outcomes of this research hold significant implications for hydrographic data practitioners. The developed AR-based visualization framework can improve the workflows of hydrographers by enhancing the accuracy and efficiency of bathymetric data interpretation. Interactively exploring complex datasets in three dimensions allows for more precise navigation, surveying, and mapping of underwater terrains. These advancements can lead to better decision-making processes and more effective management of marine resources.

At the international level, this research's contributions can influence the standards and practices of the hydrographic community. By demonstrating the practical benefits of AR in bathymetric data visualization, this thesis encourages the adoption of innovative technologies within the global hydrographic community. The methodologies and findings presented here can serve as a reference for international collaborations, fostering the development of unified approaches to hydrographic data visualization and interpretation. This can ultimately lead to more consistent and reliable nautical charts, benefiting maritime navigation, safety, and environmental monitoring.

In summary, this thesis added another knowledge to bathymetric data visualization through an innovative mixed-reality application. The research contributions provided a robust foundation for future investigations and practical implementations, aiming to improve the accuracy, efficiency, and comprehensiveness of bathymetric data interpretation.

4.2.3. Integrating XR Technologies in Hydrography: Insights from Literature and Empirical Study

Need for Innovation in Hydrographic Data Visualization

The literature review and the study findings presented a cohesive narrative that underscored the potential of XR technologies, particularly augmented reality (AR), to revolutionize hydrographic data visualization and analysis. The literature review emphasized the uniformity in hydrographic data processing and the necessity for innovation to minimize human error and reduce processing time. It suggested that traditional representation methods might not provide the best understanding of bathymetric data and advocated for immersive technologies like Extended Reality (XR) to enhance data interpretation. Inspired by these insights, the study was designed to compare the effectiveness of AR interfaces with conventional desktop monitors, aiming to provide empirical evidence on how AR could offer better visualization and understanding of bathymetric data.

Enhanced Spatial Perception and Depth Understanding

The literature review pointed out the limitations of current data analysis interfaces and the potential of XR technologies to provide unparalleled experiences in understanding geospatial data. This informed the study's focus on assessing AR's ability to improve spatial perception and depth understanding. The findings confirmed that AR interfaces offered some advantages in these areas, suggesting that AR could enhance the interpretation of complex 3D spatial relationships. This directly built upon the literature review's proposal that XR technologies could significantly improve hydrographic data visualization.

Empirical Studies and Affordances

Gibson's idea of 'affordances' (the characteristics or properties of an object or interface, that suggest how it can be used or interacted with (Gibson, 1977; see also Norman, 2013)) drive the approach this thesis, its methodology. The importance of combining empirical studies with an understanding of affordances lies in their potential to shape the design and assessment of new hydrographic interface prototypes. This approach not only opens new avenues for research but also facilitates the integration of innovative, unfamiliar interface methods with conventional practices, ensuring that new tools are both functional and effective in practical settings. Understanding affordances is critical if we are to bridge the gap between current practices and future user capabilities in professional hydrographic work environments - aligning new interface functionalities with user needs and existing workflows.

Potential of Extended Reality (XR) Technologies

The literature review proposed that XR, including virtual, mixed, and augmented reality, could transform how geospatial data was visualized and interacted with, offering new methods for understanding and utilizing data. Motivated by this proposal, the study provided empirical evidence that AR interfaces could be a practical alternative to traditional desktop methods, enhancing analytical capabilities and decision-making in hydrography. This evidence aligned with the literature review's proposition of XR technologies as transformative tools for hydrographic data visualization.

Uniformity vs. Innovation

The literature review addressed the hydrographic community's adherence to IHO standards, which leads to uniformity but potentially holds back innovation and the use of alternative technologies. This insight informed the study's exploration of AR as a non-traditional method. The study findings showed that despite the familiarity and widespread use of desktop monitors, AR interfaces offered equal or even superior performance in certain tasks. This suggested that breaking away from traditional methods could lead to innovative and more effective solutions, underscoring the importance of embracing new technologies to enhance hydrographic practices.

Future Research and Development

The literature review called for further research into advanced geospatial tasks and the potential of immersive technologies to improve data visualization and interaction. This informed the study's recommendations for future research, including integrating AR with other advanced visualization technologies, optimizing AR interface design, and exploring the long-term impacts of AR in hydrography. These recommendations aligned with the literature review's emphasis on the need for ongoing innovation and research in hydrographic data visualization.

Application and Practical Benefits

The literature review discussed the potential of XR technologies to provide new ways of understanding bathymetric data, which could benefit various applications such as maritime navigation and environmental monitoring. Inspired by this potential, the study demonstrated that AR interfaces could enhance hydrographic analysis and decision-making in practical scenarios like maritime navigation and resource management. This connection underscored the real-world applicability and benefits of the innovative technologies discussed in the literature review.

Overall, the experiment was directly inspired by the insights from the literature review, which informed its design and objectives. The integrated insights from the literature review and the study findings presented a compelling case for the adoption of XR technologies, particularly AR, in hydrographic practices. These technologies not only promised to improve data visualization and understanding but also paved the way for more precise and informed decision-making in maritime and environmental contexts.

4.3. Significance and Future Directions of the Research

The research presented in this thesis provides substantial insights into the potential of emerging tools and interfaces to enhance the visualization and interpretation of bathymetric data. This study builds upon and extends existing methods, technologies, and ideas within the realms of data visualization, mixed reality, and hydrography. By exploring the intersection of these fields, the study implements novel approaches that offer both theoretical and practical contributions to the discipline.

4.3.1. Building Upon Existing Methods and Technologies

The findings of this research are grounded in a rich group of scholarly work on data visualization and interpretation techniques. This study extends the use of augmented reality (AR) to provide innovative solutions for visualizing complex underwater environments. It builds upon concepts such as spatial data anchoring, real-time environmental feedback, and immersive user interfaces (Hedley, 2017).

The research leverages established AR frameworks, incorporating advanced visualization tools to create a more intuitive and interactive experience for users. These tools have been shown to improve the understanding of multidimensional datasets in other domains (De Back et al., 2020; Freina and Ott, 2015; Keller et al., 2021; Shelton and Hedley, 2004; Singh and Ahmad, 2024; TAN Diyuan and YU Yiqi, 2021), and this study successfully adapts them to the specific challenges of bathymetric data.

4.3.2. Future Research Directions

Several avenues for future research have been identified, each promising to advance the field of bathymetric data visualization significantly. One critical area for exploration is the integration of virtual reality (VR) technologies. VR can offer immersive experiences that allow users to gain a more profound understanding of underwater environments, thereby uncovering new insights and improving decision-making processes (Suarez-Warden et al., 2023).

Another promising direction is the use of dedicated headsets and joysticks to emulate augmented reality (AR) and virtual reality (VR) environments. These specialized tools can provide higher fidelity in spatial interactions and greater control over navigation within virtual environments. Future studies should evaluate the effectiveness of these devices in operational settings and compare their performance with traditional mobile-based AR/VR implementations (Piotrowski & Nowosielski, 2020).

4.3.3. Applied Hydrographic and Future Research Perspectives

From an applied hydrographic perspective, the affordances of AR in bathymetric data visualization should be further explored. AR can overlay digital information onto the physical world, providing contextually relevant real-time data (Shelton and Hedley, 2002). This capability can enhance situational awareness and decision-making during marine operations or research expeditions. Investigating how AR can display bathymetric data directly in the field could lead to significant operational improvements.

In addition to mixed reality and AR, other visualization interfaces should be explored to fully realize the potential of multidimensional bathymetric data. These could include immersive cave automatic virtual environments (CAVEs) (Combe et al., 2023), holographic displays, and advanced 3D projection systems. Each of these interfaces offers unique benefits and challenges. For example, CAVEs can provide a shared immersive experience for collaborative data analysis (De Back et al., 2020), while holographic displays offer intuitive, hands-free interaction with 3D data models.

4.3.4. Advanced Mixed Reality Systems and AI Integration

Future research should focus on developing and testing advanced mixed reality systems explicitly tailored for bathymetric data visualization. This includes investigating the integration of haptic feedback, eye-tracking, and adaptive interfaces to enhance user interaction and data interpretation (Kudry & Cohen, 2023). Additionally, incorporating machine learning and artificial intelligence into bathymetric data analysis and visualization could significantly enhance the ability to detect patterns and anomalies (Zhang et al., 2021). Future research could develop AI-driven tools that automatically interpret complex multidimensional datasets and provide real-time insights.

Lastly, this thesis has laid the groundwork for the innovative use of emerging tools and interfaces in bathymetric data visualization. By building upon existing technologies and exploring new directions, this research has opened up multiple pathways for future investigation. These advancements hold significant promise for improving the visualization and interpretation of bathymetric data, both in academic research and practical applications within the hydrographic industry.

4.4. References

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