Catching Jellies in Immersive Virtual Reality: A Comparative Teleoperation Study of ROVs in Underwater Capture Tasks

ANONYMOUS AUTHOR(S)*

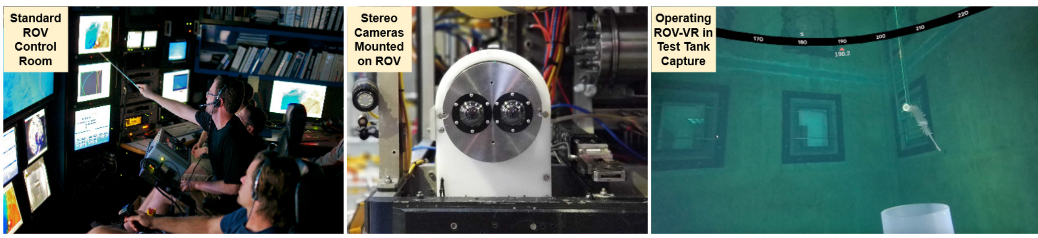

Fig. 1. A standard ROV control room is shown with a pilot and two scientists – illustrating a difficult and cognitively demanding vehicle operation task. The pilot is observing multiple monitors while operating a ROV with joysticks while a scientist is pointing to a capture target on one of the screens. In this study, we investigate the usage of stereo mounted cameras for immersive virtual reality midwater capture tasks through stereoscopic, monoscopic, and desktop teleoperation of ROVs.

Remotely Operated Vehicles (ROVs) are an essential infrastructure to any human-operated underwater missions involving the exploration and research of the ocean and beyond. ROVs are cognitively demanding to operate, hold expensive operation times, and require complex perception of the robot's position. Immersive Virtual Reality (iVR) Head-Mounted Display systems (HMDs) potentially afford a unique opportunity to ease many of these challenges. In this paper, we investigate how iVR HMDs influence operator performance through a novel telepresence system for controlling ROVs in real-time. We present a within-subjects user study [N=12] that examines three midwater capture tasks between Stereoscopic-iVR, Monoscopic-iVR, and Desktop ROV teleoperation conditions. Our findings indicate that Stereoscopic-iVR can outperform Monoscopic-iVR and Desktop ROV capture tasks, effectively doubling the efficacy of operators along with significant differences in presence, cognitive load, usability, intrinsic motivation, and cybersickness. Our research points to new opportunities for utilizing iVR in underwater ROV tasks from design to in-the-wild deployment.

CCS Concepts: • **Hardware** → *Analysis and design of emerging devices and systems*; • **Human-centered computing** → **User studies**; **Visualization design and evaluation methods**.

Additional Key Words and Phrases: Immersive Virtual Reality, Immersive Applications, Teleoperation, Telepresence, Remotely Operated Vehicle, Underwater Vehicle, Human-Operated Vehicles, Underwater Capture Tasks, Control Room, Cybersickness, Usability, Head-Mounted Display

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1 INTRODUCTION

Remotely Operated Vehicles (ROVs) are tethered, teleoperated underwater robots used in the maintenance of offshore oil and gas rigs, and in oceanic scientific research [3]. These vehicles are often equipped with cameras, lights, and sonar systems that enable a pilot to operate the ROV from the surface, allowing work to be conducted on the seafloor or at ocean depths unsafe for human divers [3, 8]. ROVs for scientific research require the use of high-resolution cameras to ensure that the pilot can view and safely navigate through the underwater environment, as well as collect marine samples. These cameras are typically broadcast-quality sensor modules fit to lenses that provide a wide-view of 86-degrees with zoom capabilities [25]. However, these wide-angle cameras do not provide enough visual context for pilots to be truly aware of their subsea environment. Existing solutions for this have involved equipping more cameras onto the ROV, aiming to provide video at all angles. "Fisheye" or ultra-wide-angle cameras have also been used to assist with providing more visual context, but video from these cameras have proven difficult to interpret when presented on 2D displays due to distortion effects.

Human factors research regarding the use of these underwater vehicles has shown decreased situational awareness, reduced spatial awareness, and increased workload for pilots due to lack of visual context, making the operation of an ROV a difficult and cognitively demanding task [13, 35]. Current research aims to address these issues for ROV pilots by exploring the use of stereoscopic cameras [7, 27, 34], and virtual reality (VR) with head-mounted displays (HMDs) [4, 7, 15, 30]. Stereoscopic cameras have been used to provide further visual context to ROV pilots by providing extensive live imagery of the subsea environment [27]. However, there are difficulties in interpreting this information due to image distortions when viewing the footage on 2D displays [34]. VR has primarily been used to provide pilots with more contextual information by utilizing reproductions of the physical environment as the VR environment (VRE) with Heads-Up Displays (HUDs) providing additional information, such as the location coordinates of the vehicle [4, 15].

While stereoscopic cameras and VR HMDs on their own do not completely address issues for ROV pilots, it is suggested that the use of these two technologies together may help resolve issues with spatial and situational awareness that result from lack of visual context [7]. However, research in this area has yet to thoroughly evaluate the effects of stereoscopic camera imagery with VR HMD systems on ROV operation. The research described in this study aims to understand how the use of an immersive VR (iVR) HMD utilizing stereoscopic camera footage from an ROV may impact ROV pilots' ability to effectively operate ROVs. In this study, the use of ROV-VR, a VR application combining HUD ROV telemetry data with live stereoscopic video footage from a miniROV, is evaluated with professional deep-sea robot operators from **REDACTED-for-anonymity** in performing midwater capture tasks within a test tank, mimicking midwater biological sample collections using detritus samplers used in oceanic research [31]. From this research, we evaluate the differences in operating the miniROV in sterescopic-iVR, monoscopic-iVR, and with desktop monitors to understand the impacts of each condition on pilots' abilities to effectively complete these tasks. Through this study, we aim to understand how these VR conditions may alleviate human factors issues with respect to operating ROVs, and how it may help ROV pilots with effectively and safely conducting oceanic research.

2 RELATED WORKS

Operating an ROV has been deemed a difficult and cognitively demanding task, as ROV pilots are required to perform multiple tasks at once with limited contextual information regarding the status of the ROV and the subsea environment [33]. Research conducted to examine human factors issues regarding ROV operation have identified lack of situational and spatial awareness due to limited information as key factors that contribute to increased cognitive workload for ROV pilots [13, 35]. Efforts have been made to increase awareness by providing increased visual and spatial information to pilots by equipping stereoscopic cameras onto ROVs and using VR HMD systems to assist with increasing the availability of contextual information [4, 15]. While efforts have been made to improve this situation for ROV pilots, current research regarding the use of stereoscopic cameras and VR HMD systems, have yet to thoroughly explore the effects of this technology on ROV pilots and their operation of these vehicles. In this section, current research regarding these VR HMD systems for ROV pilots and ROV operation will be discussed.

2.1 Remotely Operated Vehicles & Underwater Pilots

ROV pilots are required to divide their attention across multiple tasks when operating an ROV, focusing on piloting the vehicle, inspecting the subsea environment, and completing mission related tasks. Pilots will operate ROVs from a control room presenting multiple screens streaming video and telemetry information from the ROV, dispersing the attention of the pilot accordingly. This may lead the pilot to miss important information with respect to their mission or make potential errors in operation of the vehicle [33].

While the ROV control room presents multiple screens with different contextual information regarding the status of the ROV, it increases the mental workload of the pilot and does not alleviate issues that they face with situational and spatial awareness, although more contextual information is provided. Issues with spatial awareness arise due to the lack of depth cues present in the underwater environment, where shadows and occlusion are not always present to indicate depth to the pilot on the control room screens [13].Additionally, light attenuation in the ocean turns light patterns into direct reflections and forces horizons to appear shortened. Situational awareness is depreciated due to lack of perceptible depth cues, limitations in perception of contextual information provided by the multitude of control room screens, and limitations in the type and quality of information provided to the ROV pilot by video, sonar, and sensor data [9, 13, 35].

2.2 Virtual Reality for ROVs

VR solutions have aimed to help ROV pilots with situational and spatial awareness through reproducing the vehicle's environment and providing HUD interfaces with location and telemetry data [4, 7, 15, 20, 30]. Earlier VR applications provided reproductions of the ROV's environment to the pilot with additional information about the ROV's status displayed on screen [15, 20]. Hine et al.'s [15] work focused on the development of a VR application that provided a reproduction of the ROV's environment in VR and provided a grid overlay to provide location information to the pilot. These researchers aimed to increase situational awareness to the pilot by providing this map overlay over a VR reproduction of the environment to assist with understanding the ROV's subsea location. Pilots would be able to switch between viewing video from a stereoscopic camera equipped on the ROV and the VR environment in order to determine the location of the vehicle. While their study presents a novel use of VR and a stereoscopic camera for ROV operation at the time, their research does not provide information regarding the use of the system in actual ROV operations. Similarly in 1997, Pioch, Roberts and Zeltzer [20] used a VR environment to assist with training ROV pilots in maneuvering, situational awareness, and sensor integration, with situational awareness. The VR environment provided a simulation of the displays in an ROV control room along with a reproduction of a subsea environment, integrating an intelligent tutoring system to provide feedback to the pilot-in-training. A preliminary study involving the use of this system demonstrates that VR was able to help improve pilot-in-training performance in depth control and adherence to an expert path tasks, relating to maneuvering, situational awareness and sensor integration skills.

Current research continues to evaluate the use of VR systems to help ROV pilots with increasing situational and spatial awareness and to make operating ROVs more accessible and effective [4, 7, 21, 30]. Some researchers continue to replicate the ROV's subsea environment in VR, providing increased visual and contextual information through the 3D modeled environment [4, 21], while others evaluate the effects of an HUD over video imagery from the ROV's cameras [7, 30]. VR replications of the subsea environment based on stereoscopic camera imagery have been used to provide ROV pilots with more visual and contextual information [4], while newer applications of this technology have been evaluated in comparison to 2D displays [21]. Rao et al.'s [21] study examined the effects of VR and 2D indirect visual displays (IVDs) on ROV pilots' performance on subsea tasks and cognitive workload, finding that VR provides advantages to pilots over the IVD in complex subsea missions and tasks. HUDs have also been explored to assist ROV pilots with increased situational awareness, evaluating how these interfaces impact the operation of the ROV. In Solstad's [30] study, a VR system was used with a HUD over the video imaging from a fisheye camera equipped on a small ROV. They found that the VR HUD helped users with controlling the ROV by being able to view position and telemetry data from the vehicle at the same time as video imagery from the equipped cameras. Candeloro et al. [7] conducted a similar study where a VR HUD was also used, but with video footage from a stereoscopic camera equipped onto the ROV. From evaluating the use of the system in motion, inspection and manipulation tests with the ROV, it was found that it helped improve ROV operation efficiency through increased situational awareness.

Research conducted so far with respect to VR applications for ROV operations has been preliminary in nature. Existing studies focus heavily on the development of these applications, but provide little understanding as to how their applications to real-life ROV operations may impact ROV pilots' situational and spatial awareness, cognitive workload, and task performance. While the studies described above provide insight as to how VR applications may be helpful to ROV pilots, more research should be conducted to understand its impact on pilots and operation, and its application to realistic uses of ROVs.

2.3 Our Contribution

ROV pilots are essential to almost any undersea expedition. Piloting an ROV is a cognitively demanding task that requires extensive maneuvering, situational awareness, and sensor integration skills in order to safely observe and collect midwater specimen. Past research has demonstrated the benefits of utilizing VR systems for ROV simulation and training, yet there has been little work on examining the efficacy of modern iVR HMDs for telepresent ROV operation between controls. As such, the current study offers an empirical evaluation of ROV operation with iVR HMD and non-immersive desktop display through three common midwater capture tasks. We additionally explore the effects of iVR HMDs between stereoscopic and monoscopic viewing conditions to further investigate the influence of HMD interaction and visual affordances with ROV pilots. Before we do so, we provide more details on the design of our system.

3 DESIGN OF ROV-VR

Remotely Operated Vehicle Virtual Reality (ROV-VR) is a development effort aimed at both compacting ROV tele-operations centers, along with providing the pilot of the ROV with improved spatial awareness through stereo vision presented in VR. The ROV control rooms, as described in Section 2.1, often require large spaces to display all of the necessary video needed by a pilot. On research vessels, dedicated spaces are a constrained resource. By collapsing data display into a VR headset, the tele-operator station becomes more portable which frees up space on the vessel for other research needs. The VR space also enables the use of 3D interfaces and other augmented reality components that weren't possible to implement on 2D displays. Ideally, to create an immersive stereoscopic video feed in the headset, two cameras should be mounted at the average human interpupillary distance (IPD) apart. However, this is challenging to implement on a deep-sea vehicle, as submerged cameras need to be housed in pressure tolerant enclosures that make maintaining this short distance between sensors difficult.

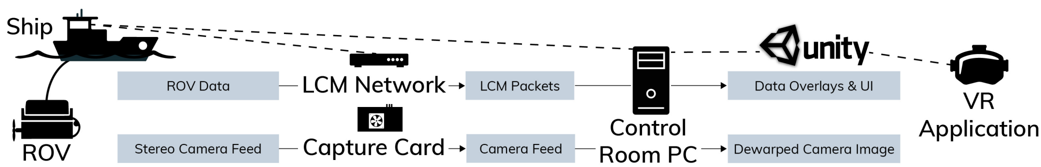

Fig. 2. ROV-VR telemetry and camera data pipelines.

3.1 System Design

ROV-VR is designed to work with the existing data pipeline used for the current ROV control room displays. The existing data pipeline revolves around two primary forms of data important to ROV pilots: ROV telemetry data (e.g. heading, depth, altitude), and auxiliary camera feeds. The telemetry data travels from the ROV sensors to the ship through fiber optic multiplexers, and is software transcoded into LCM (Lightweight Communications and Marshalling [14]) packets. These packets are streamed across the ship's local network, where an array of computers receive the packets and display the data types individually. A specially designed stereo camera system (see Figure 1) collects video in 4K resolution that has a near hemispherical (170°) field of view. That video is transmitted to the ROV control room via fiber optic cable and into video capture cards on a computer running the ROV-VR application. These capture cards store the full-resolution camera feed for archival purposes, and streams a half-resolution feed to a desktop computer that can be displayed across several screens.

ROV-VR preserves most of this system architecture, but instead of using an array of computers to handle the data types individually, all of the camera and telemetry data is fed into a single desktop which displays the data through an HMD using a custom app built in Unity. This data pipeline is illustrated in Figure 2. Since the interface in ROV-VR is not restricted to fixed 2D displays, the app allows users to rearrange the virtual data panels to match their personal preferences before use. Some data displays, such as the heading and attitude, make use of the virtual environment's flexibility and are displayed in a 3D format instead of a 2D overlay.

3.2 Stereo Processing

Footage from the stereo-fisheye camera pair is displayed in Unity through a skybox, which uses the camera feeds to create the background in the VR environment. Each camera feed requires two preprocessing steps before being projected into the skybox: undistortion and reprojection. The undistortion step accounts for deviations between the curvature in the physical and idealized fisheye lens. This deviation is modeled as a third-degree polynomial with manually tuned parameters that maps the image from the actual fisheye projection to an ideal fisheye projection. The reprojection step reprojects the image from an ideal fisheye projection to a partial spherical projection according to the process documented by Bourke [5].

When running the app in stereoscopic mode, the left image reprojection is used for the left eye display's background, and the right image reprojection is used for the right eye display's background. Since the two camera centers are approximately spaced apart by the average human IPD, this is almost enough to create a 1:1 scale immersive stereo view; however, because each person's IPD is slightly different, an x and y offset is added to each image to account for these differences. When the app is in monoscopic mode, a single camera feed is used for both backgrounds.

3.3 Pilot Interaction

In a standard ROV control room, a pilot sits in front of an expansive wall of monitors that they must frequently check to maintain awareness of the ROV's status and surroundings. A scientist sits beside them and points out targets of scientific interest for the pilot to collect. The pilot and scientist must work together to position an ROV weighing several tons to collect a free floating sample that is only a few cubic centimeters in size. Maintaining awareness of critical information while piloting the ROV and communicating with the scientist poses a significant cognitive load to the pilot. Reliance on 2D footage compounds this challenge, making it difficult to gauge the distance between the ROV and the target. Even for an experienced pilot, this limitation adds time to the capture process, where operation costs can exceed $1 USD per second and even a few seconds is enough for a specimen to swim away. ROV-VR intends to remove reliance on 2D footage and the wall of monitors by projecting the stereo footage into the VR background, creating an immersive 3D environment for pilots. This decreases the cognitive load necessary to pilot the ROV by adding depth perception to the specimen capture process, which makes it easier to gauge the distance between the ROV and the target.

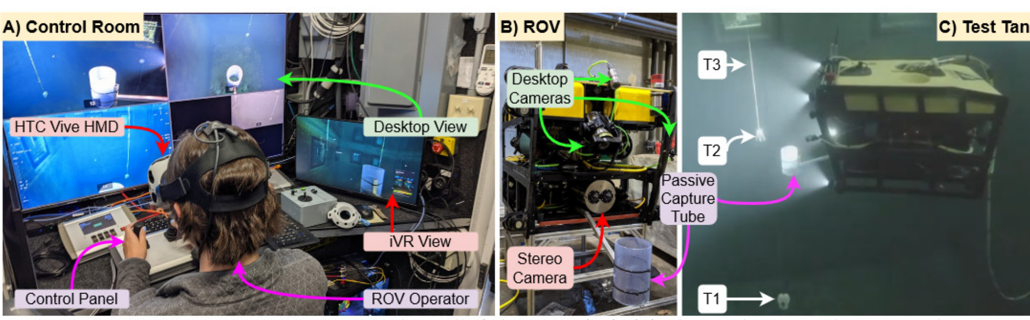

Fig. 3. An ROV Operator attempts to catch a Jellyfish target (T2). (A) Shows the control room as the operator utilizes the HTC Vive HMD with iVR view. (B) Shows the miniROV vehicle setup with passive capture tube, stereo iVR camera, and desktop view cameras. (C) Shows the operator tasks, in which participants drove the ROV to capture T1 (Larvacean "Mucus house" via 3D Printed Model), T2 (Jellyfish via bottlecap with Zip Ties), and T3 (Tomopteris Worm via feather) targets.

4 USER STUDY WITH MIDWATER CAPTURE TASKS

Our user study investigated the efficacy of operating ROVs for midwater capture tasks with ROV-VR in comparison to current best practices for ROV operation, involving high-fidelity, multi-monitor desktop displays. We also explored the differences between Monoscopic (single fisheye camera) and Stereoscopic (two adjacent fisheye cameras) views within ROV-VR to observe the affordances of HMD interaction with and without 3D to examine the effects of these configurations.

4.1 Participants

Our sample included 12 professional deep-sea robot operators (11 male, 1 female) with ages ranging from 31-65 years (M = 51.27 years, SD = 11.95 years). All 12 participants reported right-handedness. Participants varied in terms of their total experience operating underwater ROVs. Reports of weekly hours of experience with ROVs, total years of experience, and total number of dives performed ranged from 0-20 hours (M = 3.75, SD = 6.89), 0-37 years (M = 13.33, SD = 14.02), and 10-10000 dives (M = 1592.92, SD = 2866.57), respectively. Participants reported how many days had elapsed between the last time they operated an underwater ROV and the day of the experiment, ranging from 1-2556 days (M = 4877.83, SD = 848.67). Additionally, 3 participants reported having no experience with VR HMDs, 6 reported very little HMD experience, and 3 reported having some VR experience. All but one participant reported having 0 hrs of weekly VR HMD usage throughout the past month, one participant reported 2.5 hours of weekly usage. Seven of the participants had operated an ROV within the 25 hours prior to the experiment. Two participants were excluded from the study outside of the 12 included participants due sample to poor conditions in the test tank (i.e., murky water that made the task impossible) and time constraints (one participant could not finish all three conditions due to scheduling logistics). Recruitment was conducted through a local non-profit oceanographic research center via personalized emails to ROV operation staff.

4.2 Study Design

We examined three display conditions with piloting a miniROV for midwater capture: Stereoscopic-iVR HMD (Mode A), Monoscopic-iVR (Mode B), and Multimonitor Desktop (Mode C). Participants completed each mode where within-subject conditions were counterbalanced through the following configuration to account for potential order effects: ABC, ACB, BAC, BCA, CAB, and CBA (two users per order).

4.3 Participant Tasks

Participant tasks were iteratively developed with two external operators from a local non-profit oceanographic research center over the course of three months to emulate passive mid-water capture tasks using ROVs with and without iVR. Midwater ROV capture tasks are used to gather detailed information about the oceans animals through specialized non-evasive scenarios, benefiting biologists without harming the ocean's residents [23]. Common creatures collected through midwater capture tasks include a variety of "Jellies," or ocean dwelling gelatinous animals varying in size and species [23]. To emulate three common species, three targets were selected for each display condition: a Larvacea "Snotball" emulated via 3D Printed Model (T1), a Jellyfish emulated via bottlecap with Zip Ties (T2), and a Tomopterid Worm emulated via feather (T3). Each target was selected to vary common capture scenarios in specimen size, rigidness, and visibility. Experimental layout and emulated specimen sizes can be found in Figure 4. Operators were tasked to passively collect each target by navigating the ROV in order to have the emulated specimen enter the midpoint of the passive capture tube located in the front of the ROV.

4.4 Procedure

User testing was conducted during 75 minute sessions per participants at **REDACTED-for-anonymity** in a mobile control room as shown in Figure 3. A MiniROV was lifted into a simulated Test Tank with experimental setup and layout shown in Figure 4. Two researchers were present during every evaluation task, where one acted as a moderator to introduce users to the study and guide through tasks while the other recorded observational notes and handled software screen recordings. An external ROV operator was present near the Test Tank between all conditions to ensure operation conditions, lighting, and target layout remained the same between participants (while also assisting with hardware setup and take-down). Prior to user testing, this study procedure was approved by the Institutional Review Board at **REDACTED-for-anonymity** University under protocol #**REDACTED-for-anonymity**. The study proceeded as follows:

(1) Introduction: Researchers introduced themselves to the participants, obtained written consent, and sanitized all experimental equipment. Researchers then identified the three different modes (A, B, and C) to be explored in the test tank and walked users through the desktop and HMD hardware. Participants were then instructed to operate the ROV via the control room joysticks: thrusting

in each direction, identifying each relevant monitor, and viewing in all 90 degree angles when in VR to acclimate users to the environment. Researchers then identified each capture target (T1-T3) and answered any questions as necessary. Participants then performed one practice catch on T2 to acclimate to the ROV's settings (joystick gain at 55% with ROV weight trimmed heavy).

(2) Evaluation: Participants were assigned one of six counterbalanced mode orders at the start of the experiment to reduce order effect between the three conditions. For each condition, users were tasked with capturing targets in the following order with resets between: T1, T2, and T3. A capture was successfully accomplished when the participant could place the target at the midpoint of the capture tube within eight minutes. Resets consisted of piloting the ROV to the middle back of the test tank at surface elevation as shown in Figure 4. Researchers monitored desktop, VR, and test tank cameras to validate resets and successful captures. Videos of the test tank, control room, and participant view were also recorded to ensure accurate timings of capture tasks. Once each mode was successfully completed, participants filled out a ten minute performance questionnaire on a nearby desktop monitor to collect evaluation measures. This was repeated until Mode A, Mode B, and Mode C were completed per each counterbalance configuration.

(3) Wrap Up: After evaluation, participants filled out one final post-experiment survey to collect data on demographics, experience in operating ROVs, experience in utilizing VR, mode preference, and open ended responses on likes, dislikes, and feature requests with justification. Participants were also invited to discuss open-ended questions with researchers and share any other comments. At the end of all sessions, researchers debriefed with the external ROV operators to discuss re-occurring themes, patterns, and other observations from user testing.

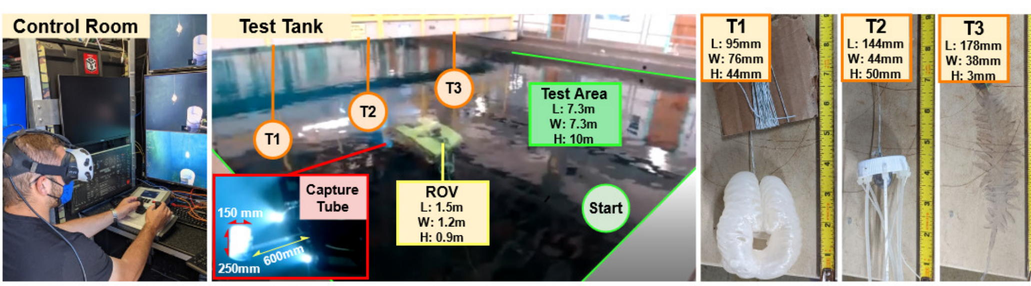

Fig. 4. Experimental layout with measurements of the control room, test tank, and capture targets (T1-T3).

4.5 Evaluation Measures

Dependent measures recorded per each mode were as follows: time to complete task, presence [32], cognitive load [12], usability [6], intrinsic motivation [19], and cybersickness [16] [17]. Contextual data was collected post-experiment around participant demographics, level of experience, and free response questions on preferences and feature requests between the three independent conditions (stereo-iVR, mono-iVR, or desktop).

Task Performance: Time to complete task was analyzed to understand the efficacy differences between stereoscopic iVR, monoscopic iVR, and desktop operation of ROVs. For each of the three capture tasks (T1-T3), a stopwatch was utilized to record the total amount of time taken for the ROV pilot to drive the ROV from the test tank starting area to acquiring the target specimen between the midpoint of the passive capture tube mounted on the ROV.

Presence: Presence within the virtual environment is often defined as a "sense of being," which has been linked to the engagement and flow of a user when performing tasks in the virtual reality [10, 29]. Utilizing iVR affords the capabilities for crafting systems that enhance presence through 6-DoF interaction within the virtual world. The Slater-Usoh-Steed Presence Questionnaire (SUS-P) was utilized to capture such presence, and has been widely validated for a variety of between-reality studies including robot operation while regarded as having the least experimental fatigue due to it's questionnaire size [28, 32].

Cognitive Load: To evaluate the difficulty and demands of the tasks provided to our users within ROV-VR, we utilize the National Aeronautics Space Administration-Task Load Index (TLX) [12]. The TLX has been widely validated as a multidimensional assessment tool to quantify a user's perception of workload, effectiveness, and performance when evaluating systems. TLX was chosen for its generalizability around operator performance with complex systems and questionnaire length. Additionally, recent research has shown that the TLX is an effective measure for comparison between VR and non-immersive spatial tasks [1].

Usability: Evaluating system usability is critical to understanding the learnability, limitations, and design needs of a system. For understanding ROV-VR, we employ John Brooke's System Usability Scale (SUS) to evaluate our system. SUS provides a "quick and dirty" yet reliable tool for measuring system usability through a 10 item questionnaire [6]. The SUS scale has been determined to be a highly robust, reliable and versatile survey for measuring system usability when compared to other usability scales [2].

Intrinsic Motivation: Intrinsic motivation or the internalization of rewards are critical in influencing task behavior with a system [26]. To explore ROV-VR's engagement between conditions, we utilize the Intrinsic Motivation Inventory (IMI) [19], a validated questionnaire for measuring a user's internalized motivations when interacting with a system. IMI has been widely utilized in a variety of past studies around VR simulation, training, and hardware operation [11, 18, 24].

Cybersickness: Simulator Sickness (SS) is a common phenomena that can affect users when utilizing virtual environments [22]. Varying displays can lead to varying amounts of symptoms such as nausea, eye strain, and disorientation – resulting in reduced or shortened user performance. While modern iVR head-mounted display systems have been leveraging higher framerates and better motion tracking to reduce SS, some virtual experience design choices can lead to higher levels of SS. To evaluate ROV-VR's effects on SS, we use the Virtual Reality Sickness Questionnaire (VRSQ) [17] (a modified version of the Simulator Sickness Questionnaire (SSQ) [16]), a 9-item, validated questionnaire for measuring negative oculomotor and disorientation symptoms on a 1-4 scale of severity to better contextualize our data collection.

5 RESULTS

For each of the dependent variables (e.g., time to successful task completion), we ran a one-way repeated measures analysis of variance (ANOVA) with the display condition as the independent variable (3 levels: stereoscopic VR, monoscopic VR, and desktop). In this section, we report upon the results that were found to be statistically significant ($p < .05$) or marginally significant ($p < .10$). We also report upon the pairwise contrasts between each combination of the three types of displays. Comprehensive measurements and analysis of our user study are shown in Table 1.

5.1 Task Completion Time

The type of display had a significant effect upon how many seconds it took for ROV pilots to successfully capture the target, $F(2,22) = 7.50$, $p < .01$, partial $\eta^2 = 0.405$. On average, participants completed the task faster in the stereoscopic condition ($M = 74.28$ seconds, $SE = 7.14$) compared to the monoscopic condition ($M = 137.36$ seconds, $SE = 15.26$, $p < .01$) and the desktop condition ($M = 158.83$ seconds, $SE = 20.91$, $p < .01$). These findings are illustrated in Figure 5.

5.2 Task Load (RTLX)

The type of display had a significant effect on perceived effort ($F(2,22) = 4.819$, $p < .05$, partial $\eta^2 = .305$) and a marginal but non-significant effect of perceived performance on the task ($F(2,22) = 3.208$,

Measure	Subscale	Stereo-iVR$^{\lambda}$	Mono-iVR$^{\lambda}$	Desktop-niVR$^{\lambda}$	p	F	partial η^2
Performance	Task Completion [s]	**74.28 (7.14)**	137.36 (15.25)	158.83 (20.91)	**	7.501	0.405
RTLX^a	Mental Demand	2.42 (0.50)	3.17 (0.46)	2.92 (0.50)	n.s.	1.235	0.101
	Physical Demand	1.75 (0.33)	2.17 (0.47)	2.50 (0.47)	n.s.	2.551	0.188
	Temporal Demand	2.33 (0.40)	2.50 (0.45)	2.67 (0.50)	n.s.	.647	0.056
	Performance	**5.67 (0.41)**	5.00 (0.37)	4.83 (0.51)	.060	3.208	0.226
	Effort	2.67 (0.43)	3.17 (0.49)	**4.08 (0.43)**	*	4.819	0.305
	Frustration	2.67 (0.50)	3.17 (0.51)	3.17 (0.51)	n.s.	1.650	0.130
SUS-P^b	Presence	**4.99 (0.26)**	3.82 (0.32)	3.19 (0.32)	***	20.144	0.647
IMI^c	Interest/Enjoyment	**5.95 (0.28)**	5.42 (0.39)	5.35 (0.35)	*	5.019	0.313
	Perceived Competence	**5.13 (0.35)**	4.63 (0.43)	4.63 (0.46)	.063	3.149	0.223
	Perceived Choice	5.43 (0.32)	5.78 (0.25)	5.47 (0.35)	n.s.	1.583	0.126
	Pressure/Tension	3.03 (0.42)	3.35 (0.43)	3.53 (0.55)	n.s.	1.772	0.139
SUS-U^d	Usability	**86.67 (3.55)**	73.54 (7.56)	71.25 (5.39)	*	3.674	0.647
VRSQ^e	Cybersickness	1.36 (0.10)	1.59 (0.14)	**1.18 (0.08)**	*	5.07	0.315
	Oculomotor	1.52 (0.16)	1.88 (0.19)	**1.31 (0.16)**	*	4.440	0.288
	Disorientation	1.23 (0.06)	1.37 (0.12)	**1.07 (0.04)**	*	3.879	0.261

Table 1. Comparisons between the Stereo-iVR (Mode A), Mono-iVR (Mode B), and Desktop-niVR (Mode C) conditions. *Note:* $^{\lambda}$ Mean (SE); *** p < 0.001; ** p < 0.01; * p < 0.05; n.s. = non-significant. Marginal p-values ($.05 < p < .10$) are reported exactly. Scale ranges from *low* to *high*: ^{a} 1 - 7, ^{b} 1 - 7, ^{c} 1 - 7, ^{d} 1 - 100, ^{e} 1 - 4.

p = .06, partial η^2 = 0.226). On average, participants perceived the task to require a significantly higher amount of effort in the desktop condition (M = 4.08, SE = 0.43) compared to the monoscopic condition (M = 3.17, SE = 0.49, $p < .05$) and the stereoscopic condition (M = 2.67, SE = 0.43, $p < .01$). On average, participants perceived their performance to be significantly more successful in the stereoscopic condition (M = 5.67, SE = 0.41) compared to the desktop display (M = 4.83, SE = 0.51, $p < .05$). These findings are illustrated in Figure 5.

There was no significant effect of display condition in the remaining NASA TLX items, consisting of mental demand, physical demand, temporal demand (i.e., time pressure), and frustration/stress.

5.3 Presence (SUS-P)

The type of display had a significant effect on presence, $F(2,22) = 20.144$, $p < .01$, partial η^2 = 0.647. On average, participants felt a significantly stronger sense of presence (i.e. they felt closer to being in the test tank as opposed to the control room) in the stereoscopic condition (M = 4.99, SE = 0.26) compared to the monoscopic (M = 3.82, SE = 0.32, $p < .01$) and desktop conditions (M = 3.19, SE = 0.32, $p < .01$). These findings are illustrated in Figure 5.

5.4 Intrinsic Motivation (IMI)

The Intrinsic Motivation Inventory is broken into four submeasures: interest/enjoyment, perceived competence, perceived choice, and pressure/tension. One-way repeated measures ANOVAs were performed on each submeasure and revealed a marginal but non-significant effect of display condition on perceived competence ($F(2,22) = 3.149$, p = .063, partial η^2 = 0.223) and a significant effect on task interest/enjoyment ($F(2,22) = 5.019$, $p < .05$, partial η^2 = 0.313). In line with the NASA TLX "perceived performance" result, participants perceived themselves to be marginally more competent at completing the task in the stereoscopic condition (M = 5.13, SE = 0.35) compared to the monoscopic (M = 4.63, SE = 0.43, $p < .05$) and desktop (M = 4.63, SE = 0.46, $p < .05$) conditions. Additionally, participants expressed significantly more interest/enjoyment in completing the task when operating in the stereoscopic condition (M = 5.95, SE = 0.28) compared to the monoscopic condition (M = 5.42, SE = 0.39, $p < .05$) and the desktop condition (M = 5.35, SE = 0.35, $p < .05$). There was no significant effect of display condition on the remaining submeasures, consisting of perceived choice and pressure/tension. These findings are noted in Table 1 and Figure 5.

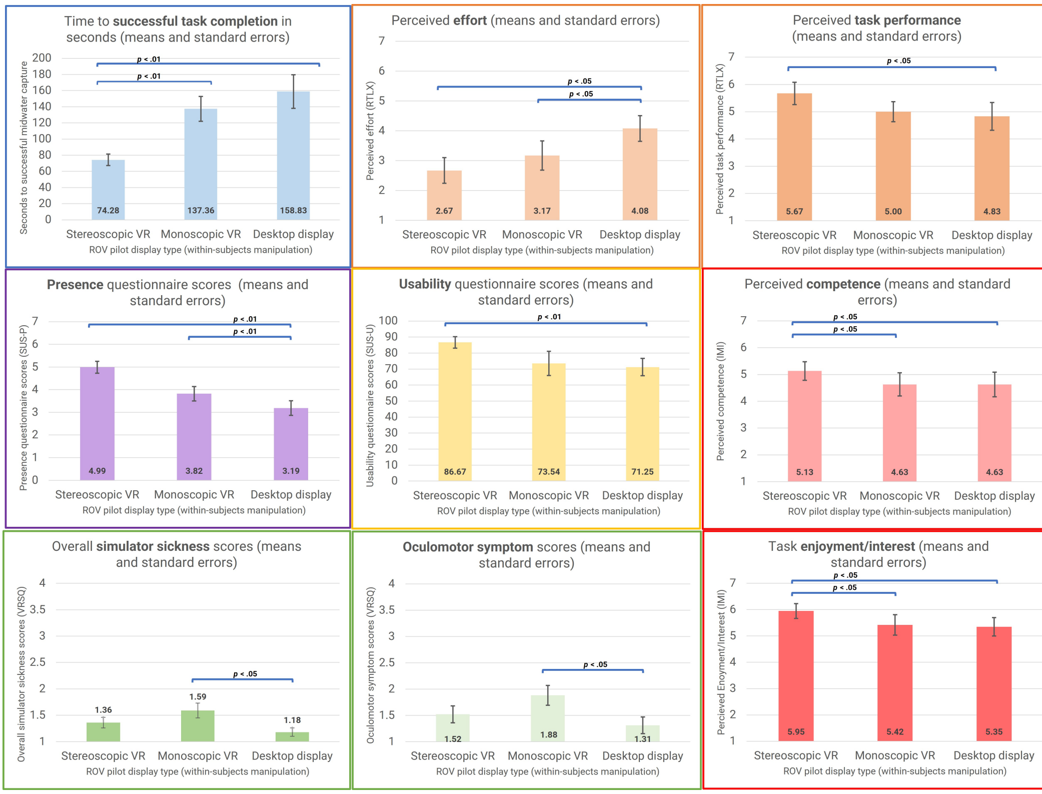

Fig. 5. Comparisons between experimental condition for significant effects in task performance (in blue), task load (in orange), presence (in purple), usability (in yellow), intrinsic motivation (in red), and simulator sickness (in green).

5.5 Usability (SUS-U)

Display condition had a significant effect on perceived usability, $F(2,22) = 3.674$, $p < .05$, partial $\eta^2 = 0.250$. Participants found the stereoscopic version of the system ($M = 86.67$, $SE = 3.55$) to be to be significantly more usable than the desktop display version ($M = 71.25$, $SE = 5.39$, p < .01). These findings are illustrated in Figure 5. It should be noted that SUS-U scores should not be interpreted as percentages, even though the scale ranges from 0-100. Furthermore, the interpretation of what constitutes acceptable usability within a system is subjective [6], so the current study has adopted the adjective ratings recommended by an empirical review of over 2,000 studies involving SUS scores [2]: scores between 52.01 and 72.75 can be considered "OK", scores above 72.75 can be considered "good", and scores above 85.58 can be considered "excellent." By this metric, the desktop display ($M = 71.25$, $SE = 5.39$) was found to be on the high margin of "OK", the monoscopic VR ($M = 73.54$, $SE = 7.56$) display was found to be "good", and the stereoscopic condition ($M = 86.67$, $SE = 3.55$) was found to be of "excellent" usability.

5.6 Cybersickness (VRSQ)

The VRSQ (Virtual Reality Sickness Questionnaire) is broken into two subscales based on symptom presentation: disorientation and oculomotor symptoms. One-way repeated measures ANOVAs were run on both subscales as well as the combined measure (averaged scores from both subscales combined). It should be noted that the scale ranges from 1-4, with "1" indicating no symptoms, "2" indicating mild symptoms, "3" indicated moderate symptoms, and "4" indicated severe symptoms.

Display condition had a significant effect on oculomotor symptoms, $F(2,22) = 4.44$, $p < .05$, partial $\eta^2 = .024$. Participants reported significantly more oculomotor symptoms in the monoscopic condition ($M = 1.88$, $SE = 0.19$) than in the desktop condition ($M = 1.31$, $SE = 0.16$, $p < .05$). Display condition also had a significant effect on disorientation symptoms, $F(2,22) = 3.88$, $p < .05$, partial $\eta^2 = .261$. Participants reported significantly more disorientation symptoms in the monoscopic condition ($M = 1.37$, $SE = 0.12$) than in the desktop condition ($M = 1.07$, $SE = 0.04$, $p < .05$). Unsurprisingly, the combined measure also revealed a significant effect of display condition, $F(2,22) = 5.07$, $p < .05$, partial $\eta^2 = .315$. Participants reported significantly more overall sickness symptoms in the monoscopic condition ($M = 1.59$, $SE = 0.14$) compared to the desktop condition ($M = 1.18$, $SE = 0.08$, $p < .05$). It should be noted that the average severity of the symptoms did not exceed 2.0 in any condition, indicating that sickness symptoms across all conditions were, at worst, mild. These findings are noted in Table 1.

5.7 Operator System Preference and Feedback

11 out of the 12 participants stated that the stereoscopic condition was their preferred mode of operation. The individual who stated that the desktop display was their preference still completed the task faster in both virtual reality conditions compared to their desktop performance.

6 DISCUSSION

We investigated the performance and perceptual influences between traditional, monoscopic, and stereoscopic telepresent operation of ROVs for common midwater capture tasks. Our comparative study revealed insights into the differences between each of these displays for operating ROVs through operator performance, task load, presence, motivation, usability, and cybersickness. We discuss our key findings, considerations for future designs, and limitations.

6.1 Key Findings

Stereoscopic iVR yields significant performance increases towards midwater ROV capture tasks for operators. Our results support the notion that using a stereoscopic display with iVR can enable pilots to track and capture targets of scientific interest with more efficiency while requiring less effort (Figure 5 and Table 1). In particular, our findings indicate that stereoscopic VR layout reduced task completion time by more than half when compared to the desktop displays, which highlights the significant potential impact stereoscopic VR can have in the oceanographic research field. The average cost of an ROV dive is extremely high (roughly $3600 per hour), and this cost can quickly go up when working further offshore or with more specialized instrumentation. Therefore even small efficiency improvements will have substantial impact on reducing the cost of scientific sampling.

Head-mounted displays and 360° monoscopic video alone are not enough to yield benefits when compared to desktop operation of ROVs. It is worth noting that incorporating both iVR and stereoscopic cameras into the piloting interface are critical to enabling this performance improvement. As shown in Figure 5, there is not a statistically significant difference between the monoscopic VR and desktop-only display modalities, but there is between the stereoscopic VR and the other two modes. Because of this, we can attribute the increase in efficiency to the combination of stereoscopic footage and VR, and not just to the use of VR.

Stereo VR teleoperation significantly enhances presence, perceived competence, and enjoyment when compared to monoscopic or desktop displays. Research has shown that heightened levels of presence can significantly influence user behavior and task performance in virtual environments [29]. Thus, our findings suggest that it is critical to adopt stereoscopic iVR when utilizing ROVs to enhance user experience.

Cybersickness symptoms were, for the most part, relatively rare and mild in their presentation across all conditions. The risk for cybersickness in this presentation was low, given that participants were seated during the experiment and all motion within the tank was relatively slow. Monoscopic virtual reality induced the most symptoms out of the three, which is not surprising. Participants may have been trying to accommodate to the "false stereoscopy" in this condition, hence the occasional mild discomfort in that condition. Overall, the VRSQ results seem to indicate that all display conditions are relatively comfortable. Some operators even indicated that the iVR HMD might reduce motion sickness by creating an "artificial horizon" to stabilize the user's reference frame of view – potentially reducing motion sickness when deployed to on the sea expeditions compared to standard monitor control rooms. Future studies could potentially investigate whether these symptoms would remain mild after longer exposure times and in-the-wild usage.

6.2 Implications for Design

The results of this study and lessons learned throughout the study design process point to several considerations for deploying VR similar to this ROV-VR system.

The distance between the cameras needed to be as close to the average person's IPD as possible in order to use stereo footage to create a 3D environment in VR at a 1:1 scale. Without proper camera spacing, a "double-vision effect" occurs and causes objects to appear twice in the scene. This effect can be mitigated to some degree by adjusting the camera centers used for computing the reprojection in software; however, the bigger the difference between the camera spacing and a user's IPD is, the smaller the range of distances from the camera this effect can be corrected for. For other applications where stereo footage is used to create an environment where having a real-world scale is important (e.g. virtual tourism, VR-based telepresence), ensuring that the proper camera spacing is employed when recording data will help to reduce this undesirable effect.

In VR environments, using a stereoscopic environment results in less cybersickness than using a monoscopic environment. Although using ROV-VR in either of the VR modes resulted in higher levels of cybersickness than using the desktop-only displays, it's worth noting that the reported levels of cybersickness are lower when using the app in stereoscopic mode than when using the app in monoscopic mode (Table 1). Although ROV-VR cybersickness may be different on a ship at sea, our results provide preliminary evidence that using a stereoscopic environment will result in less cybersickness in other immersive motion-prone environments (e.g. VR-based aviation training, FPV drones).

Using a stereoscopic environment results in a significant boost in a user's sense of presence over a monoscopic environment. While moving from a desktop-based display to a VR-based one improved our users' sense of presence, we found that the most significant increase came from moving from monoscopic to stereoscopic VR (Table 1). Although our study focused on underwater vehicle piloting, our findings may generalize to other applications that immerse people in a virtual environment via camera footage. Examples include VR conferencing, mixed-reality games, and VR educational experiences. Our findings suggest the incorporation of VR with stereo footage may boost user presence in these scenarios as well.

Using VR to provide users with depth perception of their environment can greatly boost the efficiency of task completion in teleoperated robots. While this study focused on operating underwater vehicles, navigation and manipulation in 3D environments is relevant in other domains. For example, mobile robots used for visual inspections typically rely on a monoscopic display, but our findings suggest a VR-based stereoscopic display may increase the efficiency of such inspections. These findings may also be applied to operated robot arms used for tasks such as remote surgery.

6.3 Limitations and Future Work

As with any study, there are limitations in the design that must be considered when interpreting its results. First, this study's external validity was limited in that we did not run the study at sea from a real ship's control room. Given the current limitations of how many people can safely work in enclosed spaces, it was not possible for us to run this experiment at sea. Also, we did not use live creatures as targets for the midwater capture task. We did our best to maximize the external validity of all other aspects of the study, including selecting tasks that had strong correlation to real manipulation tasks done at sea with these types of ROVs. We also recruited real ROV pilots to participate in the study to fly a real ROV (as opposed to a simulation). Using the methods from this study, it is possible for future studies to build upon this work, using the same procedures, tasks, and measures at sea or even in other remote operation contexts (e.g., flying drones, teleoperating robotic arms).

A second limitation of the current study was the relatively short period of ROV operation. Normally, ROV pilots work up to 4-hour shifts when flying ROVs at sea. The primary reason for using a relatively short duration task was that these types of midwater capture tasks are normally short duration tasks (i.e., minutes, not hours). Longer duration tasks usually involve navigating the ROV through open water (e.g., dropping to a particular location before searching for creatures), but we did not have a large enough test tank to do this. Also, we were concerned about cybersickness for our study participants so we opted to start with this short task for a first study. Future work could readily explore longer duration tasks (e.g., navigating for longer periods of time or doing more complex manipulation tasks). We would predict that cybersickness would increase with longer duration studies.

A third limitation was that we only studied three different display conditions. It would certainly be possible to run follow up studies to explore other types of VR and non-VR interfaces for ROV pilots to use (e.g., volumetric holographic displays). We chose to start with these three experimental conditions so that we could answer the more basic question of whether HMD VR displays could outperform the current best practices for ROV piloting. We opted to compare stereoscopic vs. monoscopic VR so that we could further tease apart the differences caused by the use of the second camera view. This empirical user study is just the first step in what could grow to become a much larger, richer body of research and we hope that this work encourages and enables others to join in this exploration.

7 CONCLUSION

This study investigated the performance and perceptual influences of iVR with operating ROVs for common midwater capture tasks. We designed a custom system, ROV-VR, to enable the telepresent operation of underwater ROVs between desktop, monoscopic-iVR HMD, and stereoscopic-iVR HMD conditions. Our user study examined each of these operation conditions for three common midwater capture tasks with 12 expert ROV operators. By analyzing the user study, we found that stereoscopic-iVR HMD telepresence can enhance operator performance by nearly double that of standard desktop control, while yielding significant benefits in increasing presence, usability, and motivation while also reducing task load. We also demonstrate the HMD viewing and 360-degree video alone are not significant enough to outperform desktop operation, where stereoscopic rendering is critical. Subsequently, this work is useful to inform the design and deployment of iVR ROV systems for telepresent underwater applications and beyond.

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