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

Aviv Elor
University of California, Santa Cruz
United States
aelor@ucsc.edu

Tiffany Thang
University of California, Santa Cruz
United States
tthang@ucsc.edu

Benjamin P. Hughes
University of California, Santa Cruz
United States
bephughe@ucsc.edu

Alison Crosby
University of California, Santa Cruz
United States
arcrosby@ucsc.edu

Amy Phung
Olin College of Engineering
United States
aphung@olin.edu

Everardo Gonzalez
Olin College of Engineering
United States
egonzalez@olin.edu

Kakani Katija
MBARI
United States
kakani@mbari.org

Steven H. D. Haddock
MBARI
United States
haddock@mbari.org

Benjamin E. Erwin
MBARI
United States
berwin@mbari.org

Eric J. Martin
MBARI
United States
emartin@mbari.org

Leila Takayama
University of California, Santa Cruz
United States
takayama@ucsc.edu

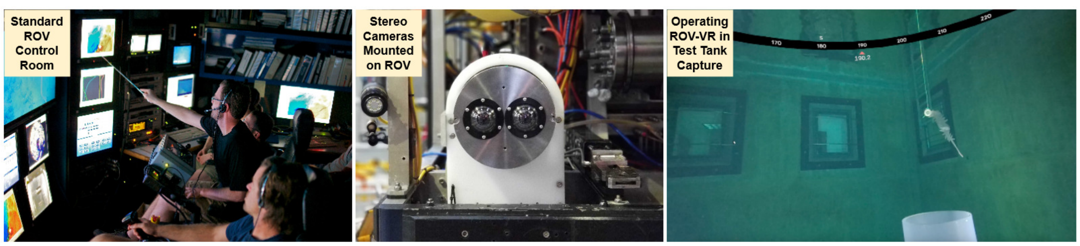

Figure 1: An ROV control room with stereo camera and ROV-VR operation is shown and explored in this study.

ABSTRACT

Remotely Operated Vehicles (ROVs) are essential to human-operated underwater expeditions in the deep sea. However, piloting an ROV to safely interact with live ecosystems is an expensive and cognitively demanding task, requiring extensive maneuvering and situational awareness. Immersive Virtual Reality (VR) Head-Mounted Displays (HMDs) could address some of these challenges. This paper investigates how VR HMDs influence operator performance through a novel telepresence system for piloting ROVs in real-time. We present an empirical user study [N=12] that examines common midwater creature capture tasks, comparing Stereoscopic-VR, Monoscopic-VR, and Desktop teleoperation conditions. Our findings indicate that Stereoscopic-VR can outperform Monoscopic-VR and Desktop ROV capture tasks, effectively doubling the efficacy of operators. We also found significant differences in presence, task load, usability, intrinsic motivation, and cybersickness. Our research points to new opportunities towards VR with ROVs.

CCS CONCEPTS

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

KEYWORDS

Immersive Virtual Reality, Immersive Applications, Teleoperation, Telepresence, Remotely Operated Vehicle, Human-Operated Vehicles, Cybersickness, Usability, Head-Mounted Display

ACM Reference Format:
Aviv Elor, Tiffany Thang, Benjamin P. Hughes, Alison Crosby, Amy Phung, Everardo Gonzalez, Kakani Katija, Steven H. D. Haddock, Benjamin E. Erwin, Eric J. Martin, and Leila Takayama. 2021. Catching Jellies in Immersive Virtual Reality: A Comparative Teleoperation Study of ROVs in Underwater Capture Tasks. In *27th ACM Symposium on Virtual Reality Software and Technology (VRST '21), December 8–10, 2021, Osaka, Japan.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3489849.3489861

VRST '21, December 8–10, 2021, Osaka, Japan

ACM ISBN 978-1-4503-9092-7/21/12…$15.00
https://doi.org/10.1145/3489849.3489861

1 INTRODUCTION

Remotely Operated Vehicles (ROVs) are tethered, teleoperated underwater robots used in the maintenance of offshore oil and gas rigs and ocean science 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, 7]. 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 and capture marine samples. These cameras are typically broadcast-quality sensor modules fit to lenses that provide a wide-view of 86-degrees with zoom capabilities [28]. However, these wide-angle cameras do not provide enough visual context for pilots to be truly aware of their subsea surroundings. Existing solutions have involved equipping more cameras onto the ROV, aiming to deliver video at all angles. "Fisheye" or ultra-wide-angle cameras have also been used to assist with providing more visual context. Still, video from these cameras has proven difficult to interpret when presented on 2D displays due to distortion effects [38].

Human factors research on the use of ROVs has shown decreased situational/spatial awareness, and high workload for pilots due to lack of visual context, making vehicle operation a difficult and cognitively demanding task [13, 39]. Current research aims to address these issues for ROV pilots by exploring the use of stereoscopic cameras [6, 30, 38] and VR with head-mounted displays (HMDs) [4, 6, 15, 33]. Stereoscopic cameras have been used to provide further visual context to ROV pilots by providing extensive live imagery of the subsea environment [30]. However, there are difficulties in interpretation due to image distortions of footage on 2D displays [38]. 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), such as the location coordinates of the vehicle [4, 15]. While stereoscopic cameras and VR HMDs on their own do not entirely address issues for ROV pilots, it is suggested that the use of these two technologies together may address issues with spatial and situational awareness that results from lack of visual context [6]. However, research in this area has yet to thoroughly evaluate the effects of stereoscopic camera imagery with VR HMD systems on ROV operation.

Our study explores how immersive VR HMD utilizing stereoscopic camera footage from an ROV may impact pilots' ability to operate ROVs. We examine a custom VR application combining HUD ROV telemetry data with live stereoscopic video footage from a ROV. For the trials, ROV operators from MBARI performed midwater capture tasks within a test tank, mimicking midwater biological sample collections using detritus samplers used in oceanic research [34]. From this research, we evaluate the differences in operating the ROV in stereoscopic-VR, monoscopic-VR, and desktop monitors to understand the impacts of each condition on pilots' abilities to complete these tasks. This study aims to understand how these VR conditions may influence human factors for operating ROVs around helping pilots to effectively and safely conduct oceanic research.

2 RELATED WORKS

Operating an ROV has been deemed a difficult and cognitively demanding task, as ROV pilots are required to perform many tasks at once with limited contextual information on the status of the ROV and the subsea environment [36]. Research conducted to examine human factors issues about ROV operation has identified lack of situational and spatial awareness due to limited information as critical factors that contribute to increased cognitive workload for pilots [13, 39].

Efforts have been made to increase awareness by providing increased visual and spatial information to pilots. One approach is mounting stereoscopic cameras onto ROVs and using VR HMD systems to assist with increasing the availability of contextual information [4, 15]. Current research has yet to thoroughly explore the effects of this technology and its impact on their operation of these vehicles. Research on VR teleoperation has provided evidence for helping to improve task performance accuracy and completion time in experimental conditions [19, 37], with few studies analyzing the effects of this technology on real-life applications. This section will discuss current research on VR teleoperation, and VR HMD systems for ROV pilots and ROV operation.

2.1 ROVs & Underwater Piloting

ROV pilots are required to divide their attention across multiple tasks when operating an ROV: piloting the vehicle, inspecting the subsea environment, and completing mission-related tasks. With these tasks, pilots operate ROVs from a control room, presenting multiple screens streaming video and telemetry information from the ROV – it is critical for pilots to manage cognitive load to monitor important information concerning their mission and reduce errors in the operation of the vehicle [36]. 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 relative distances to the pilot on the control room screens [13]. Situational awareness is degraded 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 other sensors [8, 13, 39].

2.2 Virtual Reality for Teleoperation and ROVs

VR teleoperation has been proposed as a method of increasing situational awareness and improving control and manipulation of remotely operated robots for human operators, especially as VR technologies become more accessible [12, 37]. Studies have demonstrated that such systems can improve task completion when compared to existing teleoperation methods [19, 37] and provide capabilities for improved usability and cognitive workload [37]. The incorporation of stereoscopic video imagery has also been discussed as a beneficial design consideration for VR teleoperation, but research on its application and impact is still preliminary [18, 22].

VR solutions for ROVs have aimed to help pilots with situational and spatial awareness through reproducing the vehicle's environment and providing HUD interfaces with location and telemetry data [4, 6, 15, 23, 33]. Earlier VR applications provided reproductions of the ROV's environment to the pilot with on-screen status[15]. Hine et al.'s [15] work focused on the development of a VR application that reproduced the ROV's environment to help improve the pilot's situational awareness of the subsea environment. The application allowed pilots to switch between video-feed from a stereoscopic camera equipped on the ROV and the VRE. While their work presented a novel use of stereoscopic camera for VR operation at the time, their research did not examine the usage of VR in actual ROV operations. Similarly, Pioch et al [23] used a VRE to assist with training ROV pilots in maneuvering, situational awareness, and sensor integration to provide feedback to the pilot-in-training with subsea simulated environments. A preliminary study of this VR system suggested improvements to pilot-in-training performance around in-depth control and adherence to expert maneuvering tasks.

Current research continues to evaluate the use of VR systems to help increasing situational and spatial awareness and to make operating ROVs more accessible and effective [4, 6, 24, 33]. Studies continue to replicate the ROV's subsea environment in VR, providing increased visual and contextual information through the 3D modeled environment [4, 24]. In contrast, others test the effects of a HUD over video imagery from the ROV's cameras [6, 33]. VR replications of stereoscopic camera imagery have been used to provide ROV pilots with more visual-contextual information [4], while newer applications compare stereo to 2D displays [24]. Rao et al.'s [24] study examined the effects of VR and 2D indirect visual displays (IVDs) on ROV pilots' performance on subsea tasks and cognitive workload, finding that IVDs assist operators in subsea missions. HUDs have also been explored to assist ROV pilots with increased situational awareness. In Solstad's [33] 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 control the ROV by being able to view position and telemetry data from the vehicle simultaneously as video imagery from the equipped cameras. Candeloro et al. [6] conducted a similar study where a VR HUD was also used, but with video footage from a stereoscopic camera-equipped onto the ROV. When evaluating the use of the system in motion, inspection, and manipulation tests with the ROV, VR HUDs were found to help improve ROV operation efficiency.

Research conducted so far concerning VR applications for ROV operations has been sparse. Many existing studies focus heavily on developing these applications, but provide little understanding of impact to real-life ROV operations with pilots' situational and spatial awareness, cognitive workload, and task performance. While the studies described above provide insight into how VR applications may be helpful to ROV pilots, more research should be conducted to understand its impact on pilots and VR teleoperation. In considering such, we present this study as an empirical evaluation of ROV teleoperation between VR HMD and desktop-monitor displays through three common midwater capture tasks.

3 DESIGN OF ROV-VR

Remotely Operated Vehicle Virtual Reality (ROV-VR) is a development effort aimed at compacting ROV teleoperations centers and providing ROV pilots with improved spatial awareness through stereo vision. ROV control rooms 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 teleoperator station becomes more portable, which frees up space on the vessel for other research needs. The VR space also enables 3D interfaces and other mixed reality components that could not be implemented 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.

3.1 System Design

ROV-VR is designed to work with the existing data pipeline used for current ROV control rooms. The existing data pipeline revolves around two primary forms of data essential 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 with a near hemispherical (170°) field of view. Current video latency was measured to be 249mS on a Windows based computer using an AMD Ryzen 7 2700X Eight Core processor at 3.7Ghz with 32GB RAM and an NVIDIA 2070RTX GPU. 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. Moreover, the the ROV-VR application enables 3D overlays of attitudinal data, effectively translating the standard control room of monitors into a dynamic 3D Unity environment. This data pipeline is illustrated in Figure 2.

3.2 Camera Calibration and Stereo Processing

The custom camera system utilizes two Z-Cam E2G cameras, outputting an HDMI source with a resolution of 3840 x 2160 @ 29.97 frames per second and is fitted with a Fujinon C-mount Fisheye lens. Equidistant fisheye calibration is achieved through the use of a submerged procedure involving checkered grids and calibration software called PTGui. The software maps matching pixels between the cameras, and creates a customized dewarp and blending scheme. The resulting calibration file is used by the Virtual Camera Recorder (VCR) software to remove distortion for the relative field of view being observed within the headset. Additionally, the VCR has the ability to 'tweak' various alignment parameters in real time if the viewer requires it. Because the camera utilizes fixed panoramic stereo lenses, some twisting distortion is experienced with near-field images and at the extreme edges of the field of view. Chromatic aberration is also experienced on the extreme edges.

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

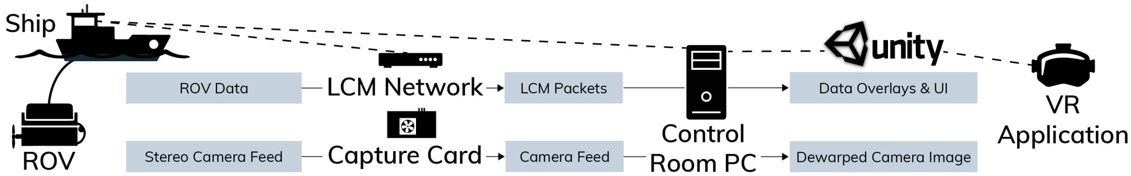

Figure 2: ROV-VR telemetry and camera data pipelines.

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 via the Bourke partial sphere process [5]. Since the two fisheye camera centers are spaced at 96mm, this enables a generalized 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 and ROV Visualization

In a standard ROV control room (Figure 1), 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. For most capture tasks, a scientist points out targets for the pilot to collect. Then the pilot must position an ROV with several tons of mass 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 task 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 escape observation or capture. ROV-VR intends to remove reliance on 2D footage and the wall of monitors by projecting the stereo footage into a VRE, creating an immersive 3D environment for pilots. This decreases the task load necessary to pilot the ROV by adding depth perception to the specimen capture process, making it easier to gauge the distance between the ROV and the target.

4 ROV-VR TELEOPERATION USER STUDY

Our user study investigated the efficacy of teleoperating ROVs for midwater capture tasks with ROV-VR compared to current best practices with 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 examine the affordances of HMD interaction.

4.1 Participants

Our sample included 12 participants (11 male, 1 female) with ages ranging from 31-65 years (M = 51.27 years, SD = 11.95 years). All participants reported right-handedness. Participants varied in 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 = 487.83, SD = 848.67). Additionally, 3 participants reported having no experience with VR HMDs, 6 had minimal, and 3 had some VR experience (though all but one user reported having 0 hours of weekly VR usage throughout the past month). Seven of the participants had operated an ROV within the 25 hours before the experiment. Recruitment was conducted through the Monterey Bay Aquarium Research Institute (MBARI), a non-profit oceanographic research center, via personalized emails to ROV operation staff.

4.2 Study Design

We examined three display conditions with piloting the MiniROV for midwater capture: Stereoscopic-VR HMD (Mode A), Monoscopic-VR (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). Data were collected over two weeks in June 2021.

4.3 Participant Tasks

Participant tasks were iteratively developed with two external operators from MBARI for three months to emulate passive mid-water capture tasks using ROVs with and without VR. Midwater ROV capture tasks are used to gather detailed information about the ocean's animals through specialized non-invasive scenarios, benefiting biologists without harming the ocean's residents [26]. Common creatures collected through midwater capture tasks include a variety of "Jellies," or ocean-dwelling gelatinous animals varying in size and species [10]. To emulate three common species, three targets were selected for each display condition: a Larvacean "Snot palace" emulated via 3D Printed Model (T1), a Jellyfish emulated via bottlecap with Zip Ties (T2), and a Tomopterid Worm emulated via feather marker (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 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 participant at MBARI in a mobile control room as shown in Figure 3. The 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-scientist to introduce users to the study and identify capture targets

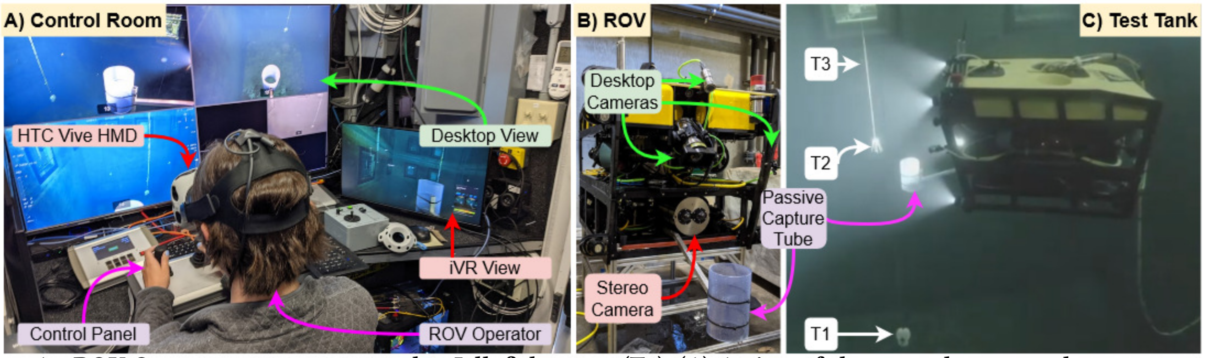

Figure 3: An ROV Operator attempts to catch a Jellyfish target (T2). (A) A view of the control room as the operator utilizes the HTC Vive HMD with VR view. (B) The MiniROV vehicle setup with passive capture tube, stereo VR camera, and desktop view cameras. (C) Shows the operator tasks, in which participants flew the ROV to capture simplified biological targets T1 (Larvacean "Mucus house" via 3D Printed Model), T2 (Jellyfish via bottlecap with zip ties), and T3 (Tomopteris Worm via feather marker) targets.

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). This study procedure was approved by the Institutional Review Board at University of California, Santa Cruz under protocol #HS3940. The study proceeded as follows:

4.4.1 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).

4.4.2 Evaluation. Participants were assigned one of six counterbalanced mode orders at the start of the experiment to reduce order effects 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 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. The test tank, control room, and participant view videos 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.

4.4.3 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.

4.5 Evaluation Measures

Dependent measures recorded per each mode were as follows: time to complete task, presence [35], cognitive load [11], usability [2], intrinsic motivation [21], and cybersickness [16, 17] between the three independent conditions (stereoscopic-VR, monoscopic-VR, or multi-monitor desktop).

Task Performance: Task completion time was analyzed to understand the efficacy differences teleoperation display types. For each of the three capture tasks (T1-T3), we used a stopwatch to record the total amount of time taken for the ROV pilot to drive the ROV from the test tank starting area to place the target specimen between the midpoint of the mounted passive capture.

Presence: Presence within the virtual environment is often defined as a "sense of being there," which has been linked to the engagement and flow of a user when performing tasks in the VR environment [32]. The Slater-Usoh-Steed Presence Questionnaire (SUS-P) was utilized to capture such presence. It has been used across a wide variety of between-reality studies, including robot operation [31, 35].

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 (NASA TLX) [11]. 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].

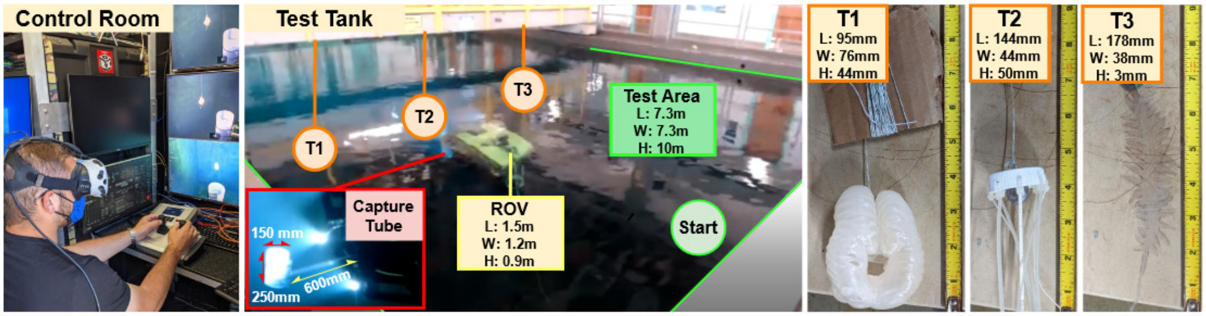

Figure 4: Experimental layout with measurements of the control room, test tank, and capture targets (T1-T3).

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 [2]. 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 insightful in understanding user behavior with a system [29]. To explore ROV-VR's engagement between conditions, we utilize the Intrinsic Motivation Inventory (IMI) [21], 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 [9, 20, 27].

Cybersickness: Cybersickness is a common phenomenon that can affect users when utilizing virtual environments [25]. 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 VR head-mounted display systems have been leveraging higher framerates and better motion tracking to reduce cybersickness, some virtual experience design choices can lead to higher levels of cybersickness. To evaluate ROV-VR's effects on cybersickness, we use the Virtual Reality Sickness Questionnaire (VRSQ) [17], 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 monitor-desktop). We report upon the results that were found to be statistically significant ($p < .05$) or marginally significant ($p < .10$) and pairwise contrasts between each combination of the three types of displays. Additionally, comprehensive measurements and statistics of our user study are shown in Table 1.

5.1 Task Completion Time

The display type 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 display type 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 ($F(2,22) = 3.208$, $p = .06$, partial $\eta^2 = 0.226$). 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 ($M = 2.67$, $SE = 0.43$, $p < .01$). 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 display type had a significant effect on presence, $F(2,22) = 20.144$, $p < .01$, partial $\eta^2 = 0.647$. 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 $\eta^2 = 0.223$) and a significant effect on task interest/enjoyment ($F(2,22) = 5.019$, $p < .05$, partial $\eta^2 = 0.313$). 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. Additionally, 11 out of the 12 participants stated that the stereoscopic condition was their preferred mode of operation. These findings are noted in Table 1 and Figure 5.

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 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 [2], 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 and 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). Additionally, 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.

6 DISCUSSION

We investigated performance and perceptual influences between monitor-desktop, monoscopic-VR, and stereoscopic-VR teleoperation of ROV midwater capture. Our comparative study revealed insights into the differences between these displays for operating ROVs through examining pilot performance, task load, presence, motivation, usability, and cybersickness. We discuss our key findings, considerations for future designs, and limitations below.

6.1 Key Findings

Stereoscopic-VR yields significant performance increases for midwater ROV capture tasks for operators. . Our results support the hypothesis that using a stereoscopic display with VR can enable pilots to track and capture targets of scientific interest with more efficiency while requiring less effort (see 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 desktop displays, highlighting the significant potential impact stereoscopic-VR can have in the oceanographic research field. The average cost of an ROV dive is exceptionally high ($3600 per hour), and this cost can quickly go up when working further offshore or with more specialized instrumentation. Therefore even minor efficiency improvements will have a substantial impact on reducing the cost of scientific sampling.

Stereoscopic cameras are critical interface components for improving operator performance towards teleoperating underwater vehicles with VR. . Head-mounted displays without stereo rendering were not enough to yield performance benefits when compared to desktop, whereas Stereo-VR teleoperation outperformed all other conditions as indicated in Figure 5. Because of this, we can attribute the increase in efficiency to the combination of stereoscopic footage and VR, not just to the use of VR. An advantage of using VR with ROVs is the ability to utilize panoramic fisheye lenses, which capture a 180 degree hemispherical view in front of the camera. Stereo-VR allows us to correlate the viewers headset position and field of view to the relative location within the field of view of the camera on the ROV. The advantage over historic attempts at stereo vision, is that head motion is much more intuitive and matches a person's natural head movements [38]. Previously, a stereo camera system would have to be physically moved through mechanical pan and tilt devices [38].

Cybersickness symptoms were, for the most part, relatively rare and mild in their presence 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-VR 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 VR 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 on 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 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 essential (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 differ on a ship at sea, our results provide preliminary evidence that using a stereoscopic environment will result in less cybersickness in other immersive motion-coupled environments (e.g., VR-based aviation training, FPV drones). In terms of movement visualization, ROV's by nature are very stable, slow-moving platforms. The movement seems very easily accepted by most viewers, and as a result we have not experienced anyone getting nauseated, even with prolonged use. Because the frame of the vehicle is within the field of view, a viewer's sense of relative motion is better understood and narrows the field of view to more well-lit regions. Poor lighting, which can result in large disparities between what each camera (eye) is filming, can cause some uncomfortable effects. Additionally, items that are too close to the cameras can also cause problems; these sometimes manifest as vertigo, and are very uncomfortable as the viewer tries to resolve the focus with their own eyes.

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. 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, drone operation, and VR educational experiences. Our findings suggest that the incorporation of VR with stereo footage may boost user presence in these scenarios.

Using VR to provide users with depth perception of their environment can significantly boost the efficiency of task completion in teleoperated robotic vehicles. While this study focused on operating underwater vehicles, navigation and manipulation in 3D environments are 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 assessments.

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. Given the current limitations of how many people can safely work in enclosed spaces (due to the COVID19 pandemic, cost, and regulations for at sea on-board staff), we could not run this experiment at sea. Also, while simulating ocean life removes confounding factors of animal behavior, 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 mimicked real manipulation tasks done at sea with these types of ROVs. We also recruited ROV pilots to participate in the study to teleoperate a physical ROV (as opposed to a simulation). Using the methods from this study, future studies can build upon this work, using the same procedures, tasks, and measures at sea or 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. Typically, 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 generally quick 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 more extended periods 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 to 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 displays to tease apart further 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 VR while operating ROVs for common midwater capture tasks.

We designed a custom system, ROV-VR, to enable the telepresence operation of underwater ROVs, and compared their operation between desktop, monoscopic-VR HMD, and stereoscopic-VR HMD conditions. Our within-subjects user study examined each operating condition with 12 ROV operators while counterbalancing display order between conditions. We found that stereoscopic-VR HMD telepresence can enhance operator performance by nearly double that of standard desktop control. stereoscopic-VR can also offer significant benefits in increasing presence, usability, and motivation while also reducing task load. We have demonstrated that HMD views alone are not significant enough to outperform desktop operation; HMDs with stereoscopic rendering is required to realize improvements in performance. Our hope is that this work will inform the design and deployment of VR systems for underwater telepresence applications and beyond.

ACKNOWLEDGMENTS

Support for the ROVVR project at MBARI is provided by the David and Lucile Packard Foundation. We would like to thank the pilots of the ROV *Doc Ricketts* for their continued support, the Olin SCOPE team members Erika Lu, Nathan Shuster, and Cameron Wierzbanowski, and their advisor Dr. Lynn Andrea Stein for their contributions to the VR-based control room. Support for the Olin SCOPE team was provided by La Fondation Dassault Systèmes.

REFERENCES

[1] A Armougum, E Orriols, A Gaston-Bellegarde, C Joie-La Marle, and P Piolino. 2019. Virtual reality: A new method to investigate cognitive load during navigation. *Journal of Environmental Psychology* 65 (2019), 101338.

[2] Aaron Bangor, Philip T. Kortum, and James T. Miller. 2008. An Empirical Evaluation of the System Usability Scale. *International Journal of Human-Computer Interaction* 24, 6 (July 2008), 574–594.

[3] Robert Bogue. 2015. Underwater robots: a review of technologies and applications. *Industrial Robot: An International Journal* 42, 3 (2015), 186–191.

[4] Francisco Bonin-Font, Miguel Massot Campos, and Antoni Burguera Burguera. 2018. ARSEA: A Virtual Reality Subsea Exploration Assistant. *IFAC-PapersOnLine* 51, 29 (2018).

[5] Paul Bourke. 2009. Omni-directional Stereoscopic Fisheye Images for Immersive Hemispherical Dome Environments.

[6] Mauro Candeloro, Eirik Valle, Michel R. Miyazaki, Roger Skjetne, Martin Ludvigsen, and Asgeir J. Sørensen. 2015. HMD as a new tool for telepresence in underwater operations and closed-loop control of ROVs. In *OCEANS 2015 - MTS/IEEE Washington*. IEEE.

[7] Romano Capocci, Gerard Dooly, Edin Omerdic, Joseph Coleman, Thomas Newe, and Daniel Toal. 2017. Inspection-Class Remotely Operated Vehicles—A Review. *Journal of Marine Science and Engineering* 5, 1 (2017), 13.

[8] Ryad Chellali, Khelifa Baizid, Gavriel Salvendy, and Michael J. Smith. 2011. What Maps and What Displays for Remote Situation Awareness and ROV Localization?. In *Human Interface and the Management of Information. Interacting with Information*, Vol. 6772. Springer, Berlin, Heidelberg, 364–372.

[9] Mary Green and Tulio Sulbaran. 2006. Motivation assessment instrument for virtual reality scheduling simulator. In *E-learn: World conference on e-learning in corporate, government, healthcare, and higher education*. Association for the Advancement of Computing in Education (AACE), 45–50.

[10] Steven HD Haddock. 2004. A golden age of gelata: past and future research on planktonic ctenophores and cnidarians. *Hydrobiologia* 530, 1 (2004), 549–556.

[11] Sandra G Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology*. Vol. 52. Elsevier, 139–183.

[12] Rebecca Hetrick, Nicholas Amerson, Boyoung Kim, Eric Rosen, Ewart J. de Visser, and Elizabeth Philips. 2020. Comparing Virtual Reality Interfaces for the Teleoperation of Robots. In *2020 Systems and Information Engineering Design Symposium (SIEDS)*.

[13] Geoffrey Ho, Nada Pavlovic, and Robert Arrabito. 2011. Human Factors Issues with Operating Unmanned Underwater Vehicles. In *Proceedings of the Human Factors and Ergonomics Society 55th Annual Meeting*, Vol. 55.

[14] Albert S. Huang, Edwin Olson, and David C. Moore. 2010. LCM: Lightweight Communications and Marshalling. In *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 4057–4062.

[15] B. P. Hine III, C. Stoker, M. Sims, D. Rasmussen, P. Hontalas, Terrence W. Fong, J. Steele, D. Barch, D. Andersen, E. Miles, and E. Nygren. 1994. The Application of Telepresence and Virtual Reality to Subsea Exploration. In *Proceedings of The 2nd Workshop on Mobile Robots for Subsea Environments, Proc. ROV'94*.

[16] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3 (1993), 203–220.

[17] Hyun K Kim, Jaehyun Park, Yeongcheol Choi, and Mungyeong Choe. 2018. Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment. *Applied ergonomics* 69 (2018), 66–73.

[18] Tomáš Kot and Petr Novák. 2018. Application of virtual reality in teleoperation of the military mobile robotic system TAROS. *International Journal of Advanced Robotic Systems* 15, 1 (2018).

[19] Jeffrey I. Lipton, Aidan J. Fay, and Daniela Rus. 2018. Baxter's Homunculus: Virtual Reality Spaces for Teleoperation in Manufacturing. *IEEE Robotics and Automation Letters* 3, 1 (2018), 179–186.

[20] Guido Makransky, Stefan Borre-Gude, and Richard E Mayer. 2019. Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments. *Journal of Computer Assisted Learning* 35, 6 (2019), 691–707.

[21] David Markland and Lew Hardy. 1997. On the factorial and construct validity of the Intrinsic Motivation Inventory: Conceptual and operational concerns. *Research quarterly for exercise and sport* 68, 1 (1997), 20–32.

[22] Yeonju Oh, Ramviyas Parasuraman, Tim Mcgraw, and Byung-Cheol Min. 2018. 360 VR Based Robot Teleoperation Interface for Virtual Tour. In *International Workshop on Virtual, Augmented and Mixed Reality for Human-Robot Interaction*.

[23] Nicholas J. Pioch, Bruce Roberts, and David Zeltzer. 1997. A virtual environment for learning to pilot remotely operated vehicles. In *International Conference on Virtual Systems and MultiMedia VSMM '97*. IEEE.

[24] Akash K. Rao, B. S. Pramod, Sushil Chandra, and Varun Dutt. 2019. *Influence of Indirect Vision and Virtual Reality Training Under Varying Manned/Unmanned Interfaces in a Complex Search-and-Shoot Simulation*. Vol. 780. Springer International Publishing, 225–235.

[25] Lisa Rebenitsch and Charles Owen. 2016. Review on cybersickness in applications and visual displays. *Virtual Reality* 20, 2 (2016), 101–125.

[26] Jason Rife and Stephen M Rock. 2001. A pilot-aid for ROV based tracking of gelatinous animals in the midwater. In *MTS/IEEE Oceans 2001. An Ocean Odyssey. Conference Proceedings (IEEE Cat. No. 01CH37295)*, Vol. 2. IEEE, 1137–1144.

[27] Hamilton Rivera-Flor, Kevin A Hernandez-Ossa, Berthil Longo, and Teodiano Bastos. 2019. Evaluation of Task Workload and Intrinsic Motivation in a Virtual Reality Simulator of Electric-Powered Wheelchairs. *Procedia Computer Science* 160 (2019), 641–646.

[28] Bruce Robison, Kim Reisenbichler, and Rob Sherlock. 2017. The Coevolution of Midwater Research and ROV Technology at MBARI. *Oceanography* 30, 4 (2017), 26–37.

[29] Richard Ryan. 2009. Self determination theory and well being. *Social Psychology* 84, 822 (2009), 848.

[30] David Scaradozzi, Laura Sorbi, and Francesco Zoppini. 2014. 3D video streaming from a Remotely Operated Vehicle. In *2014 6th European Embedded Design in Education and Research Conference (EDERC)*. 50–54.

[31] Valentin Schwind, Pascal Knierim, Nico Haas, and Niels Henze. 2019. Using Presence Questionnaires in Virtual Reality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, Glasgow Scotland Uk, 1–12.

[32] Richard Skarbez, Frederick P Brooks, Jr, and Mary C Whitton. 2017. A survey of presence and related concepts. *ACM Computing Surveys (CSUR)* 50, 6 (2017), 1–39.

[33] Torkil Eide Solstad. 2016. *Improved user-experience for control of ROVs*. Ph.D. Dissertation.

[34] Deborah K. Steinberg, Mary W. Silver, Cynthia H. Pilskaln, Susan L. Coale, and Jennifer B. Paduan. 1994. Midwater zooplankton communities on pelagic detritus (giant larvacean houses) in Monterey Bay, California. *Limnology and Oceanography* 39, 7 (nov 1994), 1606–1620.

[35] Martin Usoh, Ernest Catena, Sima Arman, and Mel Slater. 2000. Using Presence Questionnaires in Reality. *Presence: Teleoperators and Virtual Environments* 9, 5 (Oct. 2000), 497–503.

[36] A. Vasilijevic, N. Miskovic, and Z. Vukic. 2013. Comparative assessment of human machine interfaces for ROV guidance with different levels of secondary visual workload. In *21st Mediterranean Conference on Control and Automation*. IEEE, 1292–1297.

[37] David Whitney, Eric Rosen, Elizabeth Phillips, George Konidaris, and Stefanie Tellex. 2019. *Comparing Robot Grasping Teleoperation Across Desktop and Virtual Reality with ROS Reality*. 335–350.

[38] A Woods. 1997. The Application Of Stereoscopic Video to Underwater Remotely Operated Vehicles. *The APPEA Journal* 37, 1 (1997).

[39] Xian Wu, Rachel E. Stuck, Ioannis Rekleitis, and Jenay M. Beer. 2015. Towards a Framework for Human Factors in Underwater Robotics. In *Proceedings of the Human Factors and Ergonomics Society 59th Annual Meeting*, Vol. 59.

Table 1: Comparisons between the Stereo-VR (Mode A), Mono-VR (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.

Measure	Subscale	Stereo-VR$^{\lambda}$	Mono-VR$^{\lambda}$	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.	0.647	0.056
	Performance	**5.67 (0.41)**	5.00 (0.37)	4.83 (0.51)	0.060	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)	***	20.14	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)	0.063	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)**	*	5.070	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

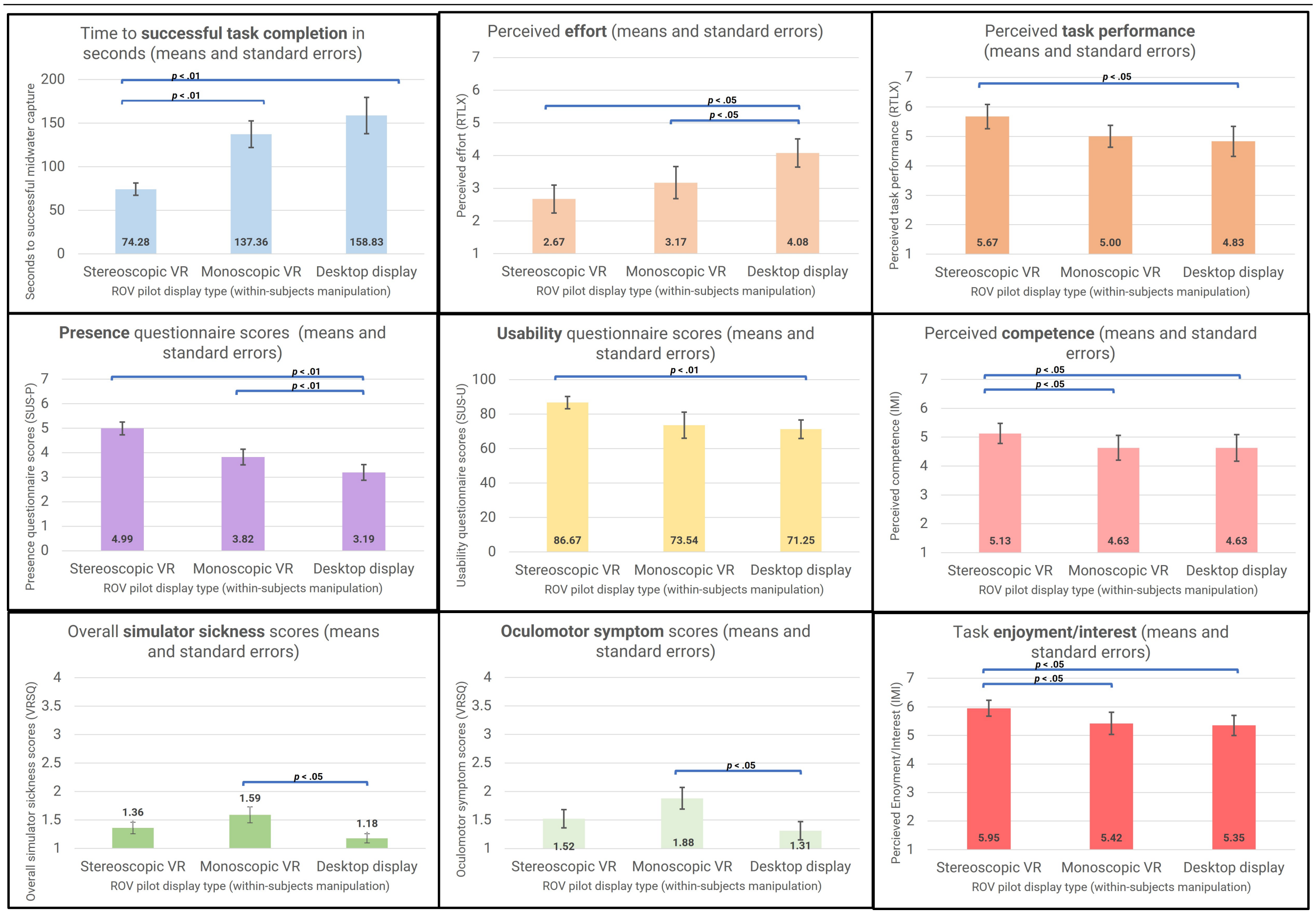

Figure 5: Comparisons between experimental condition for significant effects of task performance (in blue), task load (in orange), presence (in purple), usability (in yellow), intrinsic motivation (in red), and cybersickness (in green).