3D Interaction with Virtual Objects in Real Water

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***Abstract*—The objective of this research was to evaluate and compare perceived fatigue and usability of 3D user interfaces in and out of the water. Virtual Reality (VR) in the water has several potential applications, such as aquatic physical rehabilitation, where patients are typically standing waist or shoulder deep in a pool and performing exercises in the water. However, there have been few works that developed waterproof VR/AR systems and none of them have assessed fatigue, which has previously been shown to be a drawback in many 3D User Interfaces above water. This research presents a novel prototype system for developing waterproof VR experiences and investigates the effect of submersion in water on fatigue as compared to above water. Using a classic selection and docking task, results suggest that being underwater had no significant effect on performance, but did reduce perceived fatigue, which is important for aquatic rehabilitation. Previous 3D interaction methods that were once thought to be too fatiguing might still be viable in water.**

***Index Terms*—Virtual Reality, 3D User Interfaces, Water**

I. Introduction

3D object manipulation is one of the most common tasks in virtual reality (VR) and 3D user interfaces (3DUI). This topic has been extensively studied, resulting in many interaction methods for a variety of tasks [1]. One common complaint about 3D interfaces is fatigue - many studies have found that users often experience hand and arm fatigue during object manipulation tasks [1]–[6]. This is in part due to the effect of gravity during mid-air interactions. One way of counteracting the force of gravity is by utilizing water's buoyancy properties. For example, being underwater has proven to reduce fatigue during exercise [7]–[9] because of the weight bearing effects of buoyancy. However, it is unknown whether this reduced fatigue will extend to object manipulation tasks and how being underwater will affect task performance (e.g. completion time and accuracy), due to a lack of previous research on underwater 3DUI.

Thus, the primary focus of the presented study is on the differences between object manipulation above water and underwater, with a focus on fatigue and task performance. To this goal, we developed a waterproof VR system and an example application based on an object docking task. We investigated two classic object manipulation techniques - a virtual hand method and a raycasting method. The results of this study can be used as a starting point for future underwater VR applications in fields such as entertainment, education, exercise, SCUBA training, and aquatic physical rehabilitation.

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II. Background

A. *Motivating Application: Aquatic Physical Rehabilitation*

Aquatic rehabilitation [10] consists of performing rehabilitation exercises in a pool. Many of the exercises that patients perform in standard rehabilitation can be adapted for aquatic rehabilitation. For example, for warm-up and cool-down, low-intensity aerobic exercises such as breathing exercises, flexibility, walking, and neck, arm, and leg movements can be performed. Moreover, just as in standard rehabilitation, exercises can target joint mobility, flexor and extensor muscle strength, balance, posture, and functional activities (e.g., sitting down and standing up). For safety, patients can hold onto a flotation device as needed while performing the exercises.

There are many benefits to aquatic rehabilitation over standard rehabilitation. Because Patients are buoyant in the water, patients with physical weakness, balance issues, or fatigue [all common in multiple sclerosis (MS)] can perform physical activities for a much longer period [7]–[9]. Moreover, aquatic exercise can help to cool the body and reduce the negative effects of overheating. For example, Kargarfard et al. [11] examined the effects of aquatic rehabilitation on persons with MS, who are particularly sensitive to heat. They found that aquatic rehabilitation can improve fatigue and overall health-related quality of life. If VR can effectively be used in underwater settings, it could have significant benefits for aquatic rehabilitation, similar to VR's benefits in standard rehabilitation.

We designed the experiment described in this paper to establish the feasibility of using VR for aquatic rehabilitation tasks. Most aquatic rehabilitation exercises are with the patient's head above the water, similar to our experimental setup. Moreover, aquatic rehabilitation can include motor-control therapy for conditions such as stroke, Parkinson's disease, and multiple sclerosis. In a VR enabled motor control therapy application, patients would be required to select and manipulate virtual objects accurately and in a timely manner. This has the same goals as the task in our experiment. Thus, although our current experiment did not include patients with motor impairments, we plan to conduct studies with such populations in the near future.

B. Common Object Manipulation Techniques in 3DUI

The purpose of this section is to motivate why we chose the virtual hand and raycasting methods for our underwater study. Specifically, these two methods are arguably two of the most basic methods, but they are also two of the most influential to later methods. For the application of aquatic rehabilitation games, it is likely that one or more of these methods would be used to manipulate game objects (e.g. picking up a virtual ball from the bottom of the pool and placing it in a basket).

Mine et. al. [4] describes three ways of device based object manipulation in a virtual environment: direct manipulation (e.g., object manipulation), physical mnemonics (e.g., pull-down menu), and gestural actions (e.g., throwing object behind the body to delete it). All three ways are designed to work within arm's reach and are based on proprioception (sense of relative body position). To evaluate the core principles of proprioceptive interaction, two user studies were conducted. The first study involved virtual object docking and the second involved virtual widget interaction. In the first study, the participants completed the tasks faster when the object being manipulated was situated directly with the virtual hand, compared to having an offset from the hand. In the second study, they further rated the co-located object setting as the better method of interaction. Again, the participants completed the task better when the manipulated object was closer to the virtual hand.

Mine [1] describes several general techniques to move in a virtual environment and to select and manipulate virtual objects. Four selection techniques are described: local (i.e., Virtual Hand), at-a-distance (i.e., Raycasting), gaze, voice, and list. In our study, we use local and at-a-distance selection. Three manipulation techniques are also described: hand specified, physical controls (e.g., joystick, slider), and virtual controls. Similar to Mine's work, we implemented manipulation with a movement ratio of 2:1 (virtual:real).

Many researchers have made improvements to the Virtual Hand method to increase performance in certain scenarios. Poupyrev et. al. [12] created the Go-Go interaction technique. It is a hybrid of the Virtual Hand and Raycasting selection methods. Instead of a regular 1:1 ratio between physical hand movement and virtual hand movement, the Go-Go method scales the virtual hand movement to allow further reach. In close proximity, the Go-Go technique is the same as the Virtual Hand in that it keeps a 1:1 movement ratio. After a specific distance, the movement ratio is increased. Bubble-Cursor was created by Vanacken et. al. [2] to increase ease of selection in object dense environments. The Bubble-Cursor uses a resizable sphere as a selection area and selects the object closest to the center of the sphere. Vanacken et. al. also found that raycasting produced less fatigue than both the virtual hand and Bubble-Cursor.

C. 3DUI Fatigue

One of the classic problems in 3D user interfaces is fatigue, and there have been many previous works that introduce new techniques that lower fatigue in specific cases [2], [3], [6], [13]. All interaction techniques cause some fatigue, but 3D interaction techniques often cause greater fatigue than classical 2D interaction techniques, e.g., mouse interaction. This is due to the fact that 3D interaction typically involves holding one's arm out with no support and requiring a wider range of movement. Most 3D interfaces can be classified as either device based or gestural, both of which cause fatigue.

Gestural interfaces use a person's hands as the input device [1]. To be able to use the hand as input, previous studies have used different capture devices such as trackable gloves or cameras (e.g., Microsoft Kinect). Gestural interfaces are typically designed to be "natural", having a close resemblance to how interactions are performed in the real world (e.g., picking up an object). Kim et al. compared virtual only, virtual with passive feedback, and real environment tasks [14]. They found that the more virtual the task (i.e., having a physical object vs not having a physical object), the more difficult and more fatiguing it is. Stößel et. al. found that gestural interfaces are suitable even for the elderly [15].

Device based interfaces typically include a tangible controller, such as a hand-held wand interface as the input [1] (e.g., HTC Vive controllers). These interfaces typically have the benefit of simplicity and require button presses for most actions. As compared to gestural interfaces, a possible side effect of using an input device is increased arm fatigue compared to gestural interfaces, while gestural interfaces have more hand fatigue. The user has to support the weight of not only their arm, but also the device. Participants in Ha and Woo's study complained that holding the device in the air was tiring to participants' arms after some time [5]. In our study, we are specifically investigating fatigue in device based interfaces.

D. Underwater VR/AR Systems

There have been few works that study how VR and augmented reality (AR) can work in an underwater environment. Shark Punch [16], [17], AquaCAVE [18], DOLPHYN [19], and AREEF [20] are underwater VR/AR systems that demonstrate that underwater VR/AR games are possible. However, none of these have formally investigated usability. Moreover, none of these integrated common 3D object manipulation techniques and they did not study fatigue.

Yukai and Rekimoto define a new category of underwater robot, the "Buddy Robot". A buddy robot has two main features, the ability to give information to the user through a display and the ability to recognize and follow the user. Yukai and Rekimoto developed "Swimoid", a swim support system based on the buddy robot concept. Swimoid uses two cameras to detect color markers on the user and positions itself under the user. It has three functions: self-awareness, coaching, and game. The self-awareness function shows the video feed of the user swimming on the display. The coaching function allows a coach to give instructions to the swimmer by drawing shapes which are then shown on the display. The game function shows enemies on the display which the swimmer can make disappear by touching one of the two cameras.

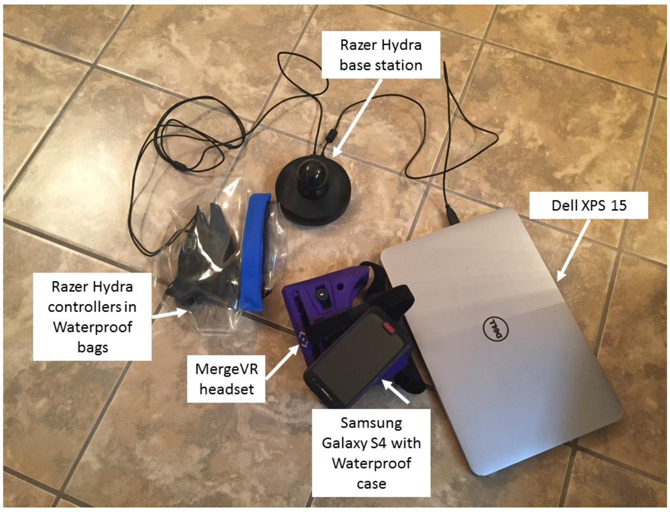

Fig. 1. Picture of system showing all components. The Razer Hydra base station is connected to the laptop through USB and has a wired connection to the Razer Hydra controllers.

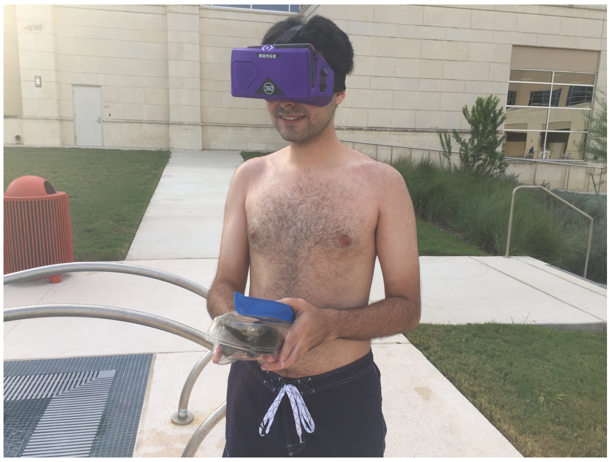

Fig. 2. Above water portion of the experiment.

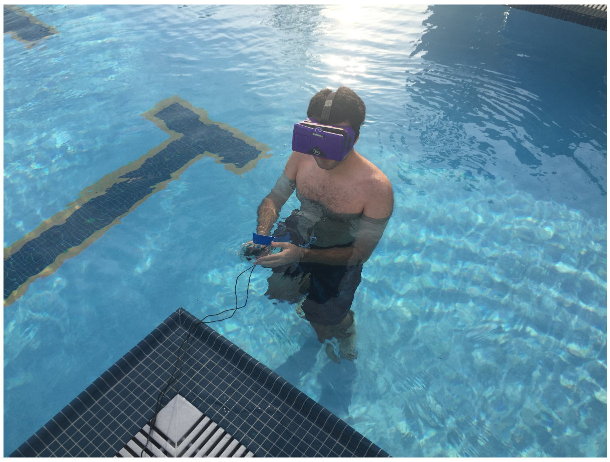

Fig. 3. Underwater portion of the experiment.

III. Materials and Methods

A. System

As seen in Figure 1, our system consists of waterproofed Razer Hydra controllers, a Samsung Galaxy S4 smartphone with a waterproof case, a Merge VR headset, and a Dell XPS 15 laptop. The laptop has an Intel 3632QM processor, Nvidia 640M graphics card, and 16GB RAM. The S4 is the primary display an performs 3 degrees of freedom head rotation tracking via the internal accelerometer, gyroscope, magnetometer sensors. The hydra controllers are placed in a waterproof bag. A hole had to be cut in the bag for the cord, and is sealed with a urethane repair adhesive and sealant. We tried to remove as much air from inside the bag as possible before sealing to reduce buoyancy and make it easier to hold. The hydra base station was not waterproofed and was placed at the edge of the pool. To stream data from the hydra to the S4, the hydra is wired to the laptop, which is connected wirelessly to the S4 with Unity's built in networking system.

B. User Study

To determine the effect of underwater 3D user interaction on fatigue and performance, we conducted a 2x2 within subjects study with 28 participants. Each participant performed 3D docking tasks in counterbalanced order both in the water and on land with two common 3D interaction methods. All participants performed the task with each interface (hand, pointer) in one location (in water or on land), before progressing to the other location.

1) Hypotheses: Because in water exercise reduces fatigue compared to above water exercise, we hypothesized that participants would feel less fatigue in water and thus achieve better performance in water. Going along with previous works [21] and pilot testing, we also believe that users will prefer a raycasting based method - Pointer - compared to virtual hand method - Hand. In summary, we hypothesize the following:

1) Users will feel less fatigue underwater than above water
2) Users will have less error underwater than above water
3) Users will prefer the Pointer method for object selection as compared to the Hand method.

2) Population: Twenty-eight college students (27 male, 1 female) took part in the study. All participants received course credit for completing the study.

3) Environment: We rented a pool at a local dive shop to use for our study. The pool is indoors and temperature controlled with a depth ranging from 3 to 12 feet. Participants were submerged up to their shoulders with their feet resting on the bottom of the pool. The water was kept at 70 degrees Fahrenheit (21 degrees Celsius) and participants were allowed to borrow a wetsuit free of charge.

4) Task: The task was to stand on the bottom of the pool in shoulder deep water and perform 3D object manipulation tasks with our waterproof VR system. The purpose of choosing this 'standing on the bottom of the pool' task over a 'free swimming task' is because most upper body aquatic rehabilitation exercises are performed standing in the pool, rather than swimming. Thus, the task design was directly influenced

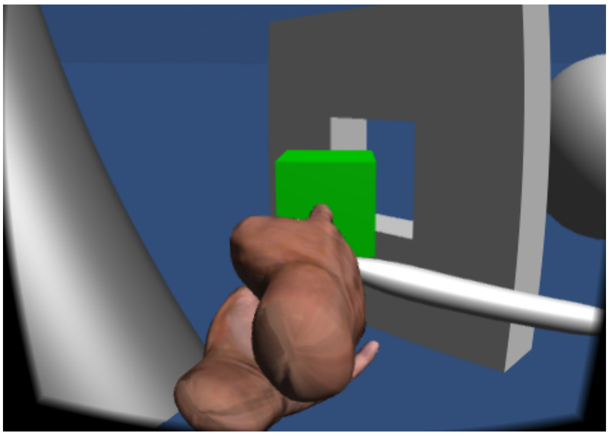

Fig. 4. Selecting the cube by pointing at the cube.

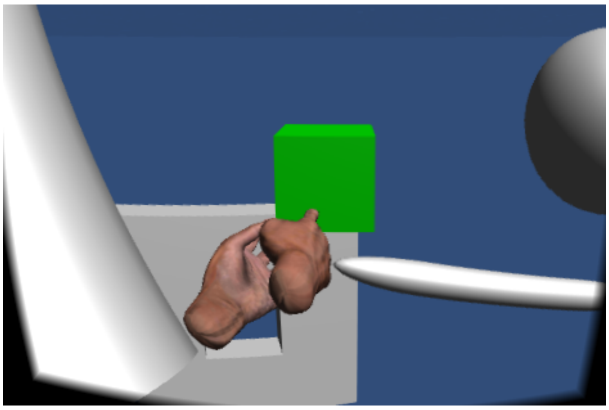

Fig. 5. Hand: Selecting the cube by intersecting the hand with the cube.

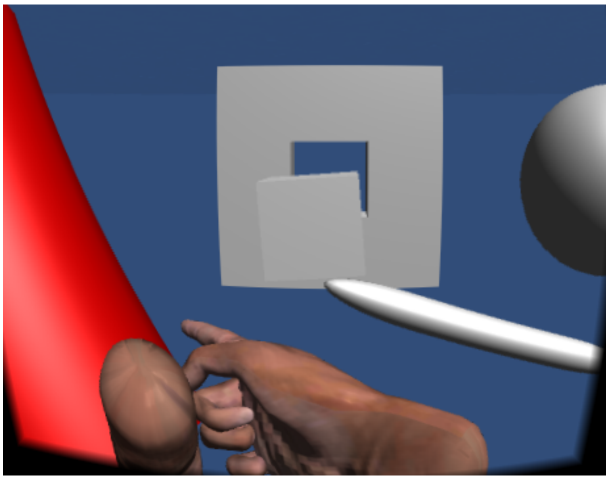

Fig. 6. The user incorrectly selects an obstacle object.

by the aquatic rehabilitation application. The participant first needs to select the cube (Fig. 4, 5). The participants are told to avoid the other objects in the scene, which turn red when selected to indicate an erroneous selection (Fig. 6). These obstacle objects were included to make the task more challenging. Participants were also told to stand in a predefined location and not move from that location while performing the task. Upon selection, the cube turns green and the participant can translate and rotate it with the controller. The objective is to insert the cube into the cube shaped hole on the wall. With 2:1 scaled movement, moving the cube into the hole requires about one arm length of movement. Upon completion, the cube goes through a spectrum of colors before resetting to its original position and the wall moves to a new location. There are five fixed locations for the wall, straight ahead (Fig. 6), ahead angled right, half distance ahead angled left (Fig. 4), down below angled up (Fig. 5), and up above angled down. The participant is instructed to complete it as accurately and quickly as possible. Upon completion of all five positions, the participant moves on to the next method/location.

5) Selection Methods: In this study, we compared two 3D selection methods: Pointer and Hand. The only feedback given in both conditions upon selection is that the cube turns from gray to green.

Pointer(P): The user must first press and hold a button to be in selection mode. Then the user must *point the hand* at the desired object to be selected. The pose of the hand model indicates the pointing direction (i.e., implemented with a raycast). When a user is pointing at the cube in selection mode, the cube turns green.

Hand(H): The user must first press and hold a button to be in selection mode. Then the user must *move the hand* to intersect with the desired object to be selected. When the the hand intersects with the cube, the cube turns green.

In both methods, once selected, the user can hold the trigger button to rotate and translate the object according to the relative position and pose of the user's controller. The object can be moved as long as it is selected, no matter where the virtual hand is located.

Both methods used a 2:1 movement ratio for translation. We implemented the 2:1 ratio because we aimed to make the task comparable to previous work, such as [1]. Thus, when a user moves their hand 1cm in the real world, the virtual hand will move 2cm in the virtual world.

6) Procedure: After signing an informed consent document, the participants first try both selection methods to become accustomed to selection and moving objects. Next, each participant completes the same task four times, twice on land and twice in the water. The order of which location is completed first is counterbalanced to reduce learning effects. During each condition, several items are automatically logged (e.g. time, error rate). In between each condition, the participants rate their fatigue. Finally, the participants decide which selection method they prefer and explain why. Each participant took on average 30 minutes to complete the study.

7) Metrics: Some parameters were automatically logged by the system: distance error, rotation error, and completion time. Each participant also answered questions about fatigue and preference.

Distance Error: We measured the distance from the final location of the cube to the optimal location of the cube. The

TABLE I
FATIGUE

Variable	Condition	Mean	Stdev.	Median
Location	Underwater	3.57	1.48	3.5
	Above Water	3.93	1.84	4
Method	Hand	3.57	1.28	4
	Pointer	3.93	1.63	4

distance is averaged across 5 trials in each condition and reported in meters.

Rotation Error: We measured the angle between the final pose of the cube to the optimal pose of the cube. The angle is averaged across 5 trials in each condition and reported in degrees.

Completion Time: We logged the amount of time it took a participant to complete the task - i.e., one docking including selection and manipulation. Completion time for a participant in a particular condition is the average of the 5 trials and reported in seconds.

Fatigue: Fatigue was rated on a Likert scale from one to seven - 1 being very low fatigue and 7 being very high fatigue. Each participant was asked to give a fatigue rating after each task completion.

Preferred Interaction Method: At the end of the study we asked participants to choose their preferred interaction method (i.e., Pointer or Hand) and their preferred environment (Above Water or Underwater).

8) Conditions: In total, each participant completed the task six times with 5 docking trials in each task for total of 30 docking trials. For each interaction method, participants were first trained how to use the interfaces and how to complete the task. For the experiment, had two independent variables, Location (Underwater (U) and Above water (A)) and Method (Hand (H) and Pointer (P)), for a total of four conditions: UP, UH, AP, AH. The only difference between P and H conditions is how objects are selected. A conditions were located on land - around four feet from the edge of the pool. U conditions were located in the shallow area of the pool, close to the edge. Every participant did every condition, but the order of the conditions was counterbalanced for each participant.

IV. RESULTS

We first conducted Shapiro-Wilk tests on the numerical and ordinal data and found them to be not normally distributed. Thus, we use non-parametric tests for analysis. For preference data, we used binomial tests.

A. Fatigue

A Friedman test showed that Method and Location have a significant effect on Fatigue (χ^2 = 11.135, p = 0.011). A post-hoc Wilcoxon test with Bonferroni correction revealed no significant difference in Method on fatigue (p = 0.45) but did show a significant effect with Location on fatigue (p = .0005, r=.688), with A (3.93) having greater average fatigue than U (3.57).

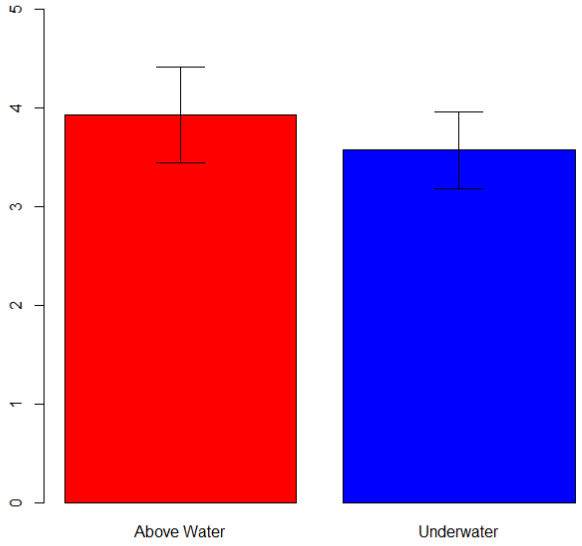

Fig. 7. Fatigue based on Location. Whiskers show confidence interval at 95%.

TABLE II
DISTANCE ERROR IN METERS

Variable	Condition	Mean	Stdev.	Median
Location	Underwater	0.230	0.197	0.139
	Above Water	0.239	0.148	0.227
Method	Hand	0.264	0.199	0.220
	Pointer	0.201	0.141	0.212

B. Completion Time, Rotation Error, and Distance Error

We found no significant differences in any of these metrics. For example, a Friedman test revealed no significant differences or interactions in Method and Location on Completion Time (χ^2 = 3.3, p = 0.348). Descriptive statistics are shown in Tables II, III, and IV,.

TABLE III
ROTATION ERROR IN DEGREES

Variable	Condition	Mean	Stdev.	Median
Location	Underwater	33.59	18.53	28.68
	Above Water	32.12	11.75	29.80
Method	Hand	32.53	18.35	29.10
	Pointer	33.35	12.42	28.73

TABLE IV
COMPLETION TIME IN SECONDS

Variable	Condition	Mean	Stdev.	Median
Location	Underwater	23.44	15.38	24.61
	Above Water	22.30	17.90	17.29
Method	Hand	23.46	11.47	23.99
	Pointer	24.32	24.29	16.21

TABLE V
PARTICIPANT PREFERENCES

	Hand	Pointer	
Underwater	2	11	13
Above Water	6	9	15
	8	20	

C. Preference

With a Cochran's Q test, we found that there was a significant difference in preference on Method (p = 0.012), but not Location (p = 0.847). A pairwise comparison using McNemar's tests with Bonferroni correction revealed that more participants prefer P compared to the H (p = 0.021, r = 0.44).

V. DISCUSSION

A. Fatigue

While we did not find fatigue differences based on Method, we did find differences based on Location. This agrees with several studies have found that aquatic exercise reduces stress on the joints compared to above water exercise [7]–[9]. As participants had to have their arms extended to move the objects, it is likely that the water supported their arm and they subsequently reported less fatigue in the U conditions. Thus, we accept Hypothesis 1: Users will feel less fatigue underwater than above water.

B. Completion Time, Distance Error, Rotation Error

It is unclear why we found no significant differences in method. Poupyrev et al. have shown that raycasting performance is highly dependent to target size and distance [21]. We believe that if the position or size of the object to be selected was changed, there would be a significant difference based on Method. However, it is unknown whether the location would make a difference once the task difficulty was increased. Thus, we intend to investigate this in the future. Thus, we cannot accept Hypothesis 2: Users will have less error underwater than above water.

C. Preference

Participants significantly preferred P compared to H. This matches up to previous research, where participants also preferred raycasting to the virtual hand [2]. In our study, some participants reported that H was "more natural", but many like P due to it being "easier" and "[requiring] less movement". Surprisingly, one participant said that H is more realistic, but still preferred P. Thus, we can accept Hypothesis 3: Users will prefer the Pointer method for object selection as compared to the Hand method.

D. The Effects of Buoyancy, Viscosity, and Temperature in Water

While it may seem like buoyancy in water was the obvious reason for the differences in fatigue, this is not necessarily the case as there are many properties of human movement in water [22] that affect movement underwater and could also have contributed to the results of the study. For example, water adds additional resistance, or drag, due to its viscosity as a body moves through it, e.g., when the user was translating objects. Moreover the thermodynamics of water causes the body to change temperature more rapidly in water. Although the temperature in and out of the water was approximately the same, the water likely felt much colder due to the thermodynamics. Due to all these differences between land and water, buoyancy was likely not the only factor that affected fatigue and performance. More research is needed to understand the reasons behind the results in our study.

VI. LIMITATIONS

There are some limitations to our study. The task the participants had to complete was short and not very fatiguing. A significantly longer and more fatiguing task would probably yield a larger effect. Another limitation is that the water of pool was only heated to 70º F, (21ºC) which all participants found very cold. While they were given time to acclimate, several participants were slightly shivering. Another limitation that affects underwater more is the tracking range of the Razer Hydra, three feet. While participants were told to stay close to the base station, due to the headset blocking vision of the real world, participants drifted at times. In the water, participants found it harder to keep a sense of location, which led to them straying further away at times. At further distances, the Razer Hydra starts to shake as the position cannot be determined as accurately. Some users commented that the shaking prompted them to reorient themselves in relation to the base station. Lastly, the waterproof bag retained air to keep water out, making it buoyant. We tried to squeeze all the air out of the bag but there was still a small amount left over. It is possible that this could have led to participants having to exert more force to keep it underwater when translating objects along negative y axis. However, based on our results, this likely was not significantly fatiguing. Regardless, we aim to improve the waterproofing technique in the future, which could further reduce fatigue.

VII. CONCLUSIONS AND FUTURE WORK

We have presented our findings on the differences in fatigue between underwater and above water 3D object manipulation. While we found no significant differences in task error or completion time, we have found that being underwater reduces fatigue in 3D interactions. With the reduced fatigue, interaction methods that have been deemed "too fatiguing" might be more effective underwater. Our future work includes investigating more fatiguing tasks, different interaction methods, and in general the effects of the properties of water on 3D interaction in VR.

The results of our study suggest that 3D interaction is feasible in water-based VR applications for persons without physical disabilities. Thus, we plan to conduct future user studies with persons in aquatic rehabilitation, such as persons with multiple sclerosis.

VIII. Acknowledgment

The authors wish to thank the participants.

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