Immersive Scuba Diving Simulator Using Virtual Reality

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ABSTRACT

We present Amphibian, a simulator to experience scuba diving virtually in a terrestrial setting. While existing diving simulators mostly focus on visual and aural displays, Amphibian simulates a wider variety of sensations experienced underwater. Users rest their torso on a motion platform to feel buoyancy. Their outstretched arms and legs are placed in a suspended harness to simulate drag as they swim. An Oculus Rift head-mounted display (HMD) and a pair of headphones delineate the visual and auditory ocean scene. Additional senses simulated in Amphibian are breath motion, temperature changes, and tactile feedback through various sensors. Twelve experienced divers compared Amphibian to real-life scuba diving. We analyzed the system factors that influenced the users' sense of *being there* while using our simulator. We present future UI improvements for enhancing immersion in VR diving simulators.

Author Keywords

Scuba diving; underwater; virtual reality; immersion; presence; buoyancy; drag force; temperature; breath-induced motion; suspension system; HMD; Oculus Rift.

ACM Classification Keywords

H.5.1. Information interfaces and presentation (e.g. , HCI): Multimedia Information Systems—*Artificial, augmented, and virtual realities*.

INTRODUCTION

Oceans are home to more biodiversity than anywhere else on the planet [1]. Fortunately, recreational diving or sport diving has enabled people to explore oceans for purposes of leisure and enjoyment. Although modern equipment and training have made diving relatively safe, divers are exposed to numerous psychosocial and physiological risks [9,25]. Additionally, diving is an expensive and time-consuming hobby that requires one to travel to large water bodies. Keeping these problems in mind, we designed a terrestrial diving simulator, with the goal of making the system as immersive as possible. We have attempted to recreate the feeling of being underwater by including elements such as buoyancy, temperature, breath control, and more. By including a wider array of senses, we go beyond providing visual and aural feedback, which are the most common aspects of currently available VR diving simulations.

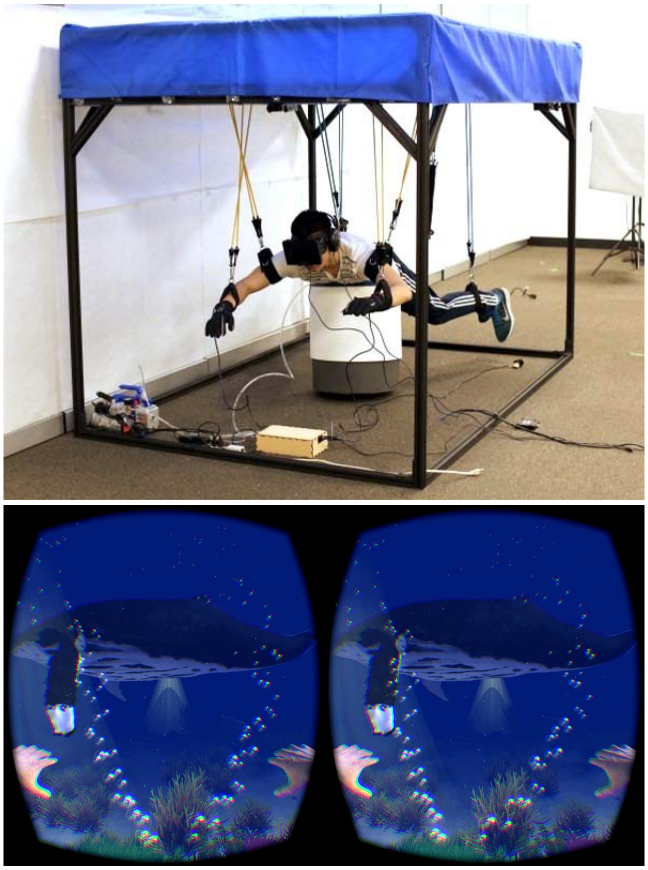

Figure 1: Amphibian is an immersive virtual reality system for experiencing scuba diving in a convenient terrestrial setting. The image shows (a) a user experiencing Amphibian, and the (b) virtual view.

Few diving simulators ask the users to swim in a pool or be immersed in a tank full of water. Though this makes the simulation feel more realistic, we believe it is not as accessible as a fully terrestrial, water-free simulator. Our goal was to make the users feel a high degree of presence in our system, without the need to jump into a pool of water.

UIST 2016, October 16–19, 2016, Tokyo, Japan.
© 2016 ACM ISBN 978-1-4503-4189-9/16/10...$15.00.
http://dx.doi.org/10.1145/2984511.2984519

Slater and Wilbur propose that the degree of a system's immersion can be objectively assessed by the characteristics of a technology [20]. For example, a low latency, high-resolution display system can deliver an extensive and vivid illusion of a virtual environment to a participant, thereby creating high immersion [20]. Presence, on the other hand, is the user's state of consciousness that accompanies immersion and is related to the sense of *being* in a place [20]. We use the terms presence and immersion as defined above and explained in the background section.

In this paper, we design and implement an immersive virtual reality system to experience scuba diving in a convenient terrestrial setting. Figure 1 shows a user lying on their torso on a motion platform to experience buoyancy. Their arms and legs are stretched out and placed in a suspended harness to simulate drag forces on the body as they swim. An Oculus Rift head-mounted display paired with a set of headphones is used to provide visual and audio feedback. The user also wears gloves with embedded flex sensors and IMUs that track their hand movements to allow navigation in the underwater environment. Peltier modules attached to the gloves touch the user's wrists to simulate temperature changes as they dive deeper into the water. An inflatable airbag placed under the user's torso is controlled by their breathing and allows them to move their virtual body up and down.

We report on a user study with 12 skilled divers where we compared the *immersiveness* of the system to real-life scuba diving, and gathered feedback on how *present* the divers felt while using our system. In general, participants found the ability to move up and down with their breathing very realistic. They appreciated the visual and audio simulation, and suggested improvements for the suspension system. Other sensory simulations had mixed reactions. The overall reported sense of presence was moderately high (4.96/7).

The contributions of our work are twofold. We believe our strongest contribution is the simulation of unusual sensations – breathing buoyancy control, temperature and haptics, which have not been significantly explored in other related simulators. We chose the specific case of scuba diving, which was amenable to trying out the various sensory stimuli devices that provide feedback for highly specific senses but add up to create a multi-sensory system. We also evaluated the system with 12 divers who provided feedback about immersiveness of our system as compared to real life scuba diving. This helped us identify aspects of the system that influenced different presence factors and led us to uncover future UI improvements.

BACKGROUND AND RELATED WORK

Immersion and Presence in Virtual Reality Systems

Researchers have proposed several definitions of presence related to VR [8,12,17,18,20–22,24]. Steuer [21] refers to a telepresence system as a combination of the ability to produce a sensorially rich mediated environment (called *vividness*), and the degree to which users of a medium can influence the mediated environment (*interactivity*). Witmer and Singer [24] link the effectiveness of virtual environments (VEs) to the sense of presence reported by users in those VEs. They define presence as the *"subjective experience of being in one place or environment, even when physically situated in another."* Nichols [12] underlined three measures that can determine presence in a virtual environment: *"the feeling of being, the feeling that it was a place that participants visited rather than saw, and the feeling that they had forgotten the real world whilst in the VE."*

In this paper, we chose to employ the terms *immersion* and *presence* as distinguished by Slater and Wilbur [18] as they help clearly define our system and enable us to compare it to real-life scuba diving in our qualitative study. Immersion describes the extent to which the VR systems are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant. *Inclusive* indicates the degree to which physical reality is shut out. *Extensive* indicates the range of sensory modalities accommodated. *Surrounding* signifies the extent to which this virtual reality is panoramic rather than limited to a narrow field. *Vivid* indicates the resolution, fidelity, and variety of energy simulated within a particular modality (for example, the visual and color resolution).

Presence is a user's response to an immersive system. It includes three aspects: the sense of *being there*, the extent to which the virtual environment takes precedence over the real one, and the way users refer to their experience as having been to a place vs having seen a place [4]. Presence is an increasing function of immersion. For example, a system that accommodates multiple sensory modalities (extensive) will increase the user's sense of being there.

Scuba Diving Simulations

There are many PC games that simulate maritime environments [26–28]. These games usually include a player that navigates through interactive visuals in the form of marine wildlife, shipwrecks and other underwater elements like rocks, caves etc. Though the visuals and graphics of these games are compelling—and also inspire the visuals in our system—the games are designed to primarily stimulate the visual and auditory human senses. A more immersive simulation would need to include other additional senses like kinesthetic or temperature to better recreate the feeling of being underwater.

Frohlich [7] and Takala et al. [23] use a cave-like simulation system to depict an underwater environment. They enclose a user in a room and project 3D images of the marine world onto the walls to create an inclusive simulation. In Slater's terms, such environments are more *inclusive* than PC games, as they completely enclose the users in a virtual world. However, more human senses can be targeted to make simulations more *extensive*. For instance, in Takala et al's simulation, the user stands on the ground and wears gesture detection gloves whereas in Amphibian, the user rests their torso on a platform with their arms and legs suspended in a harness system, mimicking the swimming posture more closely.

Some systems immerse users in a pool or a tank of water to simulate the experience of being in the ocean. For instance, Blum et al. used augmented reality and a waterproof head-mounted display to visually enhance a regular swimming pool with virtual maritime objects displayed on a mobile PC device mounted in front of a diving mask [2]. Similarly, AquaCAVE is a computer-augmented water tank with rear-projection acrylic walls that surround a swimmer, providing a cave-like immersive stereoscopic projection environment [29]. These systems feel realistic because the user is actually immersed in water, something that is difficult to simulate on land. In Amphibian, we create a feeling of being immersed in water, in a terrestrial setting by using various methods and targeting multiple senses as described below.

Virtual Reality Kinesthetic Systems

Edward Link created the first commercial flight simulator in 1929 [Wikipedia]. Consisting of an entirely electromechanical setup using motors, rudder and a steering column, it was used to train pilots in WWII. Since then, continuous developments have led to the creation of highly immersive kinesthetic VR systems for flight simulation, surgery, rehabilitation, space technologies, military training, manufacturing and entertainment [13,16,19,55].

Structurally, our system has elements similar to those in Birdly [14], Swimming Across the Pacific [6] and Haptic Turk [5]. Birdly is an art installation that simulates flying using an Oculus Rift headset and an inverted massage chair like surface. The user mimics a bird by resting their torso on the chair with their arms stretched out. Their hands rest on a plastic hand-rest with buttons to start or stop flight. The user navigates by using their arms and hands, flapping them slowly to gain altitude while the Oculus Rift displays a bird's-eye view of their virtual surroundings. The system uses sensory-motor coupling to map the movements of the bird to the corresponding physical movements of the user.

Swimming Across the Pacific (SAP) is another artistic installation that simulates swimming. It suspends the user from an 8ft cubic volume structure via a hang gliding harness. The pulleys and cords provide counter forces to the user's movement to simulate drag forces. The graphic system renders the virtual swimmer and the scenery.

Haptic Turk uses humans known as *turkers* or human actuators to create physical motion for the person wearing an HMD in a Wizard of Oz manner. The turkers lift the person using their hands and provide kinesthetic feedback by pushing, rotating or tilting a person as required by the visual scene shown on the Oculus Rift display. Amphibian stimulates the kinesthetic sense through an automated platform instead of motion administered by human actuators.

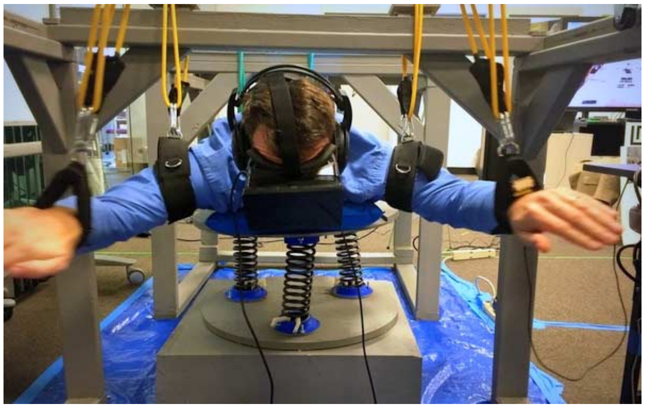

Figure 2: Preliminary prototype consisting of a smaller wooden rig, is experienced by a user during evaluation.

SYSTEM DESIGN AND IMPLEMENTATION

Preliminary Prototype

To get feedback on our idea, we designed an initial prototype of the system where the user rested on a torso support and had their arms and legs suspended from elastic bands (Figure 2). The torso support consisted of three large springs on a wooden base and was topped with a water bed (see figure). The elastic bands were suspended from a wooden rig. We attached an accelerometer to the user's wrist to get preliminary hand movement data. Breathing based buoyancy control and temperature simulation were not implemented in this prototype.

We deployed the system in our open lab space during the lab's semi-annual open house. A total of 36 participants, both divers and non-divers, tried our system for a rough duration of 10 minutes each. In general, reactions were positive. Most people appreciated how they were able to feel buoyant and navigate in the underwater environment. Some people remarked that the combination of the waterbed with the torso base made them feel weightless as they swam through the VR application. We also received some suggestions from users that helped inform the final system design (described below). A primary concern that emerged from the feedback was the restricted arm movement due to the small size of the wooden frame. Additionally, the swim gesture was not smooth as the wooden sliders attached to the bands had a lot of friction. Another suggestion by a participant was used to create a swiveling base that provides realistic 3D spatial movements as explained below. The suggestion to connect breathing and buoyancy came from two divers.

System UI Design

The objective of this work was to recreate the sensations and physical conditions of scuba diving in a convenient terrestrial setting. We simulated sensory distortions as experienced underwater. For example, due to differences in reflectivity, light transmission and varied magnification, we experience poor contrast, severely reduced visual range and

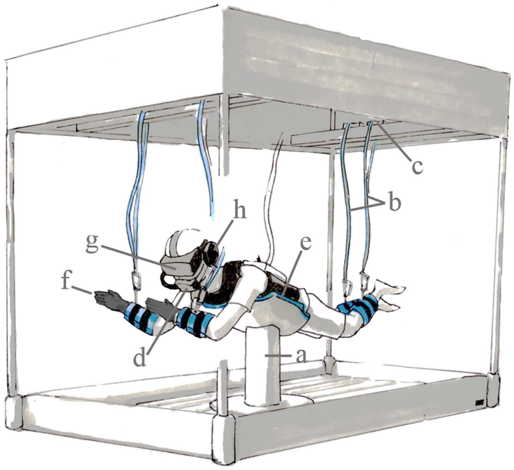

Figure 3: Amphibian incorporates six different sensations. *Kinesthesia* and *Balance* are simulated by the torso base and provide buoyancy (a, Figure 5a), elastic bands move in the slider assembly to provide drag as the user swims (b and c resp., Figure 4), a mouth piece measures breathing (d, Figure 5b), and an inflatable cushion moves up and down with the user's breathing (e, Figure 5a). Gloves (f) are used for motion sensing and *Temperature* simulation (Figure 6). *Visual* and *Audio* sensations are provided by the Oculus Rift (g, Figure 1b) and noise-canceling headphones (h). An inflatable textured ball provides *Force* feedback when a user interacts with an underwater object (Figure 7).

impaired object magnification [30]. Our hearing underwater is quite distorted too. Since sound travels five times faster in water than in air, we cannot localize sound effectively underwater. Our other senses are also severely muted. We cannot smell at all underwater and we avoid tasting things. Our sense of touch is considerably reduced since water causes fingertips to prune, thereby reducing sensitivity.

Other sensory modalities like thermoception (sense of temperature), equilibrioception (sense of balance), and proprioception (sense of kinesthesia) are relatively unaltered, but are nevertheless stimulated. For instance, in the underwater environment, divers move freely in the 3D space, while using their breath to rise and fall slightly and balance themselves. Divers also feel a noticeable decrease in temperature as they go deeper in the water [31].

Since there is so much more to the experience of being underwater than just visual feedback, we designed our system to incorporate six different sensations, namely– opthalmoception (sight), audioception (hearing), tactioception (touch), proprioception (kinesthetic sense), thermoception (temperature), and equilibrioception (balance) (Figure 3). Out of these senses, prior VR research scuba simulations have not focused much on equilibrioception, proprioception and thermoception.

Kinesthesia and Balance. The final design was a culmination of input from the first author's personal experience with scuba diving, feedback from the preliminary evaluation of the first prototype, and inspiration from the kinesthetic systems (Birdly, SAP) discussed in the Related Work section.

Figure 4: Horizontal sliders move in the XY plane as the user moves their arms to mimic a swimming gesture. The sliders are attached to resistance bands (in yellow), which are attached to user's arms and legs.

The final prototype had a robust and smoothly moving non-motorized structure, assembled with 80/20 beams and roller wheels [32] (Figure 1). For the design of the harness, we considered two forces exerted by water on the submerged human body – buoyant forces, which provide counter effect to gravity, and drag forces, which restrict voluntary motion. We attached resistance bands to the user's limbs to counter motion and simulate drag forces (see figure). For attaching the bands to the user's arms and legs, we used long neoprene sleeves of varying resistance. This helped to distribute the forces uniformly across each limb. The bands were suspended from the horizontal sliders in the harness, which moved in the assembly in the XY plane (Figure 4). To simulate buoyant forces, we used a buoy stool as torso support. The buoy had a vertical damping effect that felt buoyant when the user lied on it. It also provided unrestricted swivel in 3D space.

Besides limb motion, scuba diving relies heavily on breathing for buoyancy control. To simulate that, we implemented breath motion in our system. By attaching an accurate gas flow sensor to the user's mouth-piece, we measured the amount of air inhaled and exhaled (Figure 5b). The torso rest contained an inflatable cushion that was connected to an air and vacuum pump (Figure 5a). This cushion inflated and deflated proportionally to the air inhaled/ exhaled by the user. This caused the user's body to rise up and fall down in sync with their breathing, similar to how it happens in water. The breath sensor also caused the appearance of air bubbles in the Oculus app.

Temperature. Real oceans have thermoclines which cause the temperature to decrease at certain depths from the sea surface [15]. Since the Oculus app allowed the user to dive deep, we simulated temperature changes using Peltier thermoelectric cooler modules [33]. Additionally, we added cool gel packs to the neoprene bands to enhance the overall coldness sensation.

Regarding temperature simulation, we needed to determine where to attach the Peltier module on the user's body and how many to use. We did not want to overburden the user

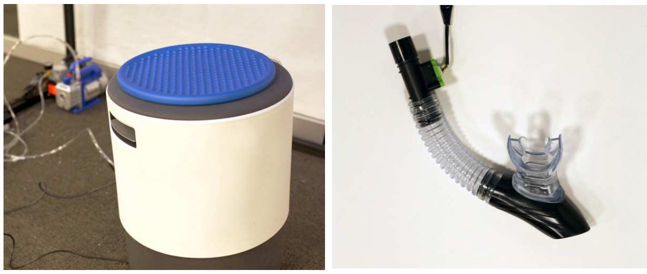

Figure 5: (a) Inflatable cushion that rises and falls in sync with the user's breathing, while their torso rests on it. (b) Mouth piece with the gas flow sensor that measures the amount of air inhaled and exhaled, which in turn controls the cushion inflation.

by putting multiple Peltier modules on the body. The wrist is known to be one of the prime cooling points of the body due to the radial artery being close to the skin's surface. Studies show that local cold on the wrist can give a body-wide sensation of coolness [11]. Since the user already needed to wear gloves, we decided to attach one Peltier module to each glove's wrist to simulate fall in temperature with depth.

Audio-Visual. In the Oculus Rift app, the user swam in a confined area underwater with rocky topography that changed with depth. The ocean also contained a variety of aquatic plants, schools of small fish, and two big fish that appeared randomly during the user's exploration. The addition of these elements was inspired by various scuba diving games mentioned earlier in the related work. Similar to real-life diving, our app was dimly lit to simulate reduced visual range. The sound was also tuned to the underwater environment. Particularly significant was the loud sound of user's air bubbles corresponding to the user's real world breath exhalation. The noise-canceling headphones ensured the user's presence in the simulation by shutting out sounds from the real world.

To mimic a real diving scenario, the user's hands and movements were tracked and displayed in the Oculus app. We chose to include only the user's arms and hands in the simulation, as other parts of the body are relatively less visible during diving. The hands were tracked using gloves that contained an IMU and flex sensors (Figure 6). The IMUs tracked the hand orientation and acceleration while the flex sensors were used to determine bend in the fingers for recognizing grasping gesture. This tracking data was sent to an Arduino microcontroller where virtual hand movement was calculated and relayed to the Oculus app (described below). The combination of hand orientation and threshold for acceleration in different directions allowed us to detect basic swim gestures needed to move forward, left, right, up, and down. For example, to move left, the user pushed the water right with his left hand and the palm facing inward.

Touch. The system also provided physical feedback when the user interacted with underwater objects such as rocks or marine life. This two-way interaction between the user and the aquatic environment, has not been previously implemented in VR scuba simulations. The user could grab virtual objects with their hands, and tactile feedback was provided by inflating a silicon ball situated close to the palm of the glove (Figure 7). When released, the virtual object fell to the ocean bed and the ball deflated. To test a different implementation of haptic feedback, we also created a glove with silicon air pockets on the palm that inflated or deflated based on the user's interaction with objects in the aquatic environment. A few preliminary tests showed that the inflatable ball provided greater haptic feedback than the inflated glove pocket.

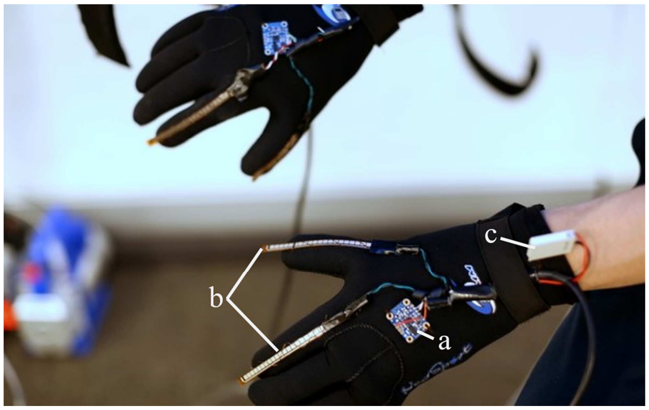

Figure 6: Gloves worn by the user. Each glove contains (a) an IMU to track the user's hand orientation, (b) flex sensors to track finger bend, and (c) a Peltier module, to simulate temperature change.

Summary. In summary, to increase the immersion of the system as described by Slater and Wilbur [18], we designed for a range of senses, namely the sense of sight, hearing, kinesthetic sense, temperature, tactile and balance (*Extensive*). The user rested horizontally on a swiveling torso support with their arms and legs suspended in a harness system. They wore an Oculus Rift DK2 and noise-canceling headphones to see panoramic visuals and hear vivid sounds from the underwater environment (*Surrounding*). This helped to keep the user engaged and away from the visual and auditory cues from reality (*Inclusive*). The fidelity and resolution of the audio-visual simulation with the magnificent ocean diversity and high quality sounds, and the range of movements supported by the suspension system gave a vivid representation of the virtual world (*Vivid*).

System Implementation

Software – Computer and Oculus Rift Assembly. We modified an application downloaded from the Oculus app store [4] with full permission from the developer. The app was edited in the Unity game engine [34] with 3D models downloaded from the Unity Assets store. The hands were created from the Leap Motion SDK v2.3 [35] and manipulated using the Leap Motion API reference v2.3 [36]. The app was run on a laptop PC connected to the Oculus Rift DK 2. A breathing sensor (Sensirion gas sensor [37]) was attached to a snorkel mouthpiece worn by the user (Figure 5b). The data from the breathing sensor was sent to the app where it triggered the appearance of bubbles. We used BOHM noise-canceling headphones [38] to emphasize the

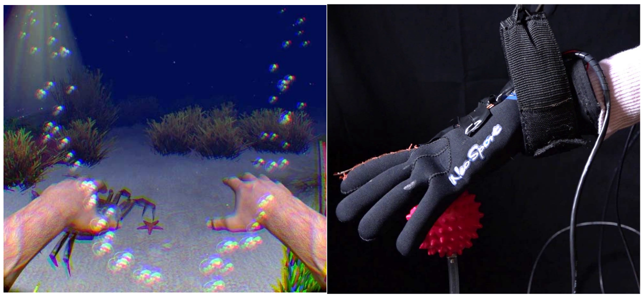

Figure 7: The user is about to pick up a crab from the ocean bed (a) in VR view, and (b) haptic feedback provided using a textured ball. As soon as the user grabs the crab, the ball inflates. When they release the crab, the ball deflates.

ocean sounds by keeping the surrounding noise to a minimum. The computer exchanged data with the Arduino microcontroller located in the control box (details below).

Hardware – Glove Assembly. The user wore NeoSport 3mm Neoprene gloves [39] that are commonly used in scuba diving. Each glove contained one 9-DOF BNO055 IMU Fusion sensor, two long flex sensors and one Peltier module, all easily and cheaply available components, procured from Adafruit Inc. [40]. These sensors exchanged data with the Arduino microcontroller in the control box. To simplify the assembly, we used two flex sensors instead of five, one for the user's thumb and one for the four fingers. This two-pivoted virtual hand system successfully allowed the user to grab objects underwater by making a grasping gesture with their hand. For physical feedback, we used a 3.5 inch textured hand massage ball. The amount of air in the ball was regulated by the microcontroller and pump assembly.

Control Box – Interface Assembly. The control box contained an Arduino Due microcontroller [41], a JBtek 4 channel 5V DC relay module [42], and two Pneumadyne 2-way solenoid valves to regulate air flow [43] (Figure 8). The Arduino microcontroller was used for the bi-directional interface between the software and the hardware components of the system. The microcontroller relayed the IMU and finger tracking data from the gloves, along with the calculated swim gestures, to the computer running the Oculus app. It also received the temperature, breathing sensor and the inflatable ball data from the computer. The temperature simulation data was sent to the relay module, which selectively turned on the Peltier modules located on the gloves. The deeper the user was in the virtual ocean, the longer the time for which the Peltier modules were turned on, making the user feel coolness. The breathing sensor data triggered the relays driving the pneumatic valves. The pneumatic valves controlled the air supply from/to air and vacuum pumps and to/from the inflatable cushion. When the user inhaled, the air supply valve turned on and the vacuum valve turned off, and vice versa. This caused the cushion to inflate and deflate, and the user moved up and down. Similar mechanism was used to inflate and deflate the silicon ball. When the user grabbed an underwater object, the ball inflated from the data sent through the computer, and vice versa.

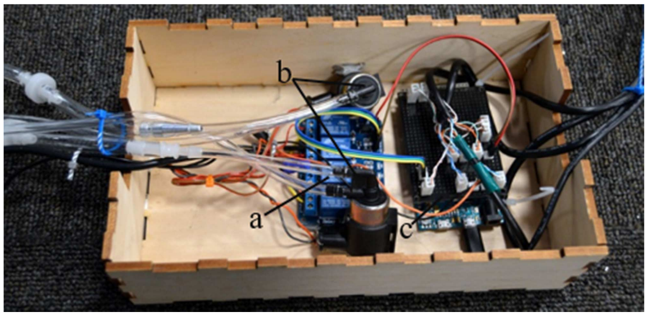

Figure 8: Control box for interfacing, containing (a) the blue relay module, (b) two solenoid valves and (c) the Arduino microcontroller.

Kinesthetic System. The suspension system was built using the 80/20 aluminum set [32]. We used sixteen 1515 [44] and 1530 [45] beams of different lengths to build the support structure; a combination of 12 roller wheels [46] and four 1530 beams were used to make the sliding assembly. Black Mountain resistance bands [47] were attached to the user's limbs with neoprene sleeves. These sleeves also contained therapeutic packs [48] to enhance the cooling sensation. The packs were cooled in the refrigerator before being added to the sleeves. The sliding assembly was covered with a blue stitched fabric (Figure 1). Besides providing an aesthetic look, light passing through the fabric added a blueish sea color to the assembly, creating a space that felt inviting.

The torso support base used a Turnstone buoy [49] with an inflatable cushion [50] placed on it. The cushion was connected to the pneumatic values and subsequently to the vacuum and air pumps using transparent Polyurethane air pipes. We used an ultra-quiet Champion Sports 1/8 HP air compressor [51] and the Zeny 3.5 CFM vacuum pump [52]. The same pumps were also connected to the inflatable ball with separate valves.

EVALUATION

To validate the concept of using a VR system for scuba diving, evaluate how our system compares to the real life scuba diving, and gather feedback for improvements, we conducted a qualitative study with 12 experienced divers.

Method

Participants

Twelve volunteers (ages 18-61, 5 female) were recruited through email and social media. Participants' average height and weight was 173.3cm (*SD*=11.0, range 157-188) and 72.3kg (*SD*=14.6, range 50-96). All of them had completed at least 25 dives before the study (*M*=166.2, *SD*=166.6, range 35-500). They were compensated $20 for their time.

System Setup and Performance

We ran our app on a MacBook Pro laptop with a 2.2 GHz processor, 16GB RAM and Intel Iris Pro Graphics. On 10 runs of the app for 15 mins each, the average frame rate was 17.21fps. Though this frame rate is low for most VR apps, it was effective for our simulation, as it displayed an exaggerated slowness of movement underwater which corresponded with real diving fairly well. The time it took to visually display an initiated body motion was ~100ms, and consisted of lag due to a low power GPU that impacted rendering, and the hardware-software interface.

Procedure

The study procedure took 45 minutes on average, and included the system experience, an open-ended interview and two questionnaires. At the beginning of the system experience, participants received instructions to complete a set of tasks in the simulator. The tasks were: swim forward and up, turn right and left, grab a virtual crab, and breathe in and out through a snorkel to control the rise and fall of the virtual body. Additional instructions were verbally provided as needed, necessitating the use of non-noise canceling headphones. After the initial 5 to 7 minutes of training, participants explored the system for another 10 minutes.

Following the experience, we conducted an open-ended interview to collect general comments on the system, suggestions for improvements and potential applications. The participants filled out a demographic questionnaire and a custom modified version of the Witmer and Singer questionnaire [24], containing specific questions on how each part of our system compared to real scuba diving. Finally, they filled out a standard iGroup Presence Questionnaire [53] that contained questions related to presence. The questionnaires were presented on a computer and the entire session was video recorded.

Data and Analysis

The interviews were transcribed and subjected to an iterative coding process [3]: (i) one researcher developed an initial codebook for each of the 3 sections of the interview; (ii) two independent coders analyzed up to three randomly selected transcripts and met and refined the code set; (iii) the final code set was applied to the remaining transcripts by two independent coders. For this last step, Krippendorff's alpha across all codes was on average 0.72 (*SD*=0.10). Conflicting code assignments were resolved through consensus between the two coders.

We grouped the questions in the Witmer and Singer questionnaire into seven different categories based on our codes (Kinesthesia, Visual, Audio, Temperature, Tactile, Breathing, and Delay). We took the average of 7-point rating scale responses across all questions in a single category. For questions that would fit in multiple categories, we took a weighted average in those categories. For example, for the question *'how closely were you able to examine objects?'* we assigned a weight of 0.5 to Visual and Tactile scores while calculating the averages. We then converted the responses from each category into a 3-point scale: high [5-7], medium [3-5) and low [1-3) and analyzed the distribution of participants across this scale using a chi-square (χ^2) test. We also grouped questions from the presence questionnaire into factors specified by iGroup (General Presence, Spatial Presence, Involvement, and Realness) and reported averages of 7-point scale responses to all questions in those categories. The factors are explained in the section below.

Findings

Is a VR scuba diving simulator useful?

In general, all 12 participants thought that a VR scuba diving simulator would be useful for people. When asked about potential applications, all 12 wanted to employ our system to increase exposure and accessibility for: (i) people who are either uncomfortable or scared of water (5 of 12 participants), (ii) people who have never dived before or kids who are not old enough to dive but want to try it (5), or (iii) people who used to dive but cannot dive anymore due to health or decompression issues (2). Other suggested uses were gaming and entertainment (8), training (6), education (2), and therapy (2).

"People who would want to see how diving is like or are learning diving, it [simulator] would be good. People get scared when they are placed in open water for the first time. They get stuck." (P8)

"I used to dive with a dive manual that showed pictures of fish to help identify them. This could be so cool for that case." (P11)

How 'present' were the participants using our system?

Factor analysis of the iGroup presence questionnaire (IPQ) explains three loaded factors that collectively affect Presence: *Spatial Presence*, which is related to the sense of acting in the virtual space instead of operating something from outside [53], *Involvement,* which describes the attention given to the real and virtual environments [24,53] during the simulation and, *Realness*, which is the comparison of experience in the real-life and the virtual world [24,53]. The overall rating of presence is then derived from the average of ratings in all question in these three factors, and ratings for another question on general presence.

The reported overall rating of presence across all participants was 4.96/7 (*SD*=0.06). Across the three factors, the average ratings were moderately high for Spatial Presence (*M*=4.92/7, *SD*=1.26) and Involvement (*M*=5.12/7, *SD*=1.22), but low for Realness (*M*=3.44/7, SD=*1.20*). Through this result, we can infer that though the participants were engaged and present in the virtual underwater world, they did not behave as if they were scuba diving for real. In other words, their actions in the simulator were not natural.

How 'immersive' was our system?

We analyzed the responses to the immersion questionnaire and the qualitative feedback from the open-ended interview in emergent themes, to understand the results of the presence questionnaire, as presented above.

Breathing. Across all participants, breathing simulation was considered the most realistic part of the system. Eleven participants appreciated the breathing simulation, out of which seven explicitly said the rise and fall of the body through breathing made them feel like they were really scuba diving. P7 used breathing to adjust their buoyancy in VR and said, *"it is pretty close to [real diving] when you get neutrally buoyant underwater."* However, 4 participants had mixed reactions to the speed of upward and downward motion related to breathing. For example, P4 said: *"it was a*

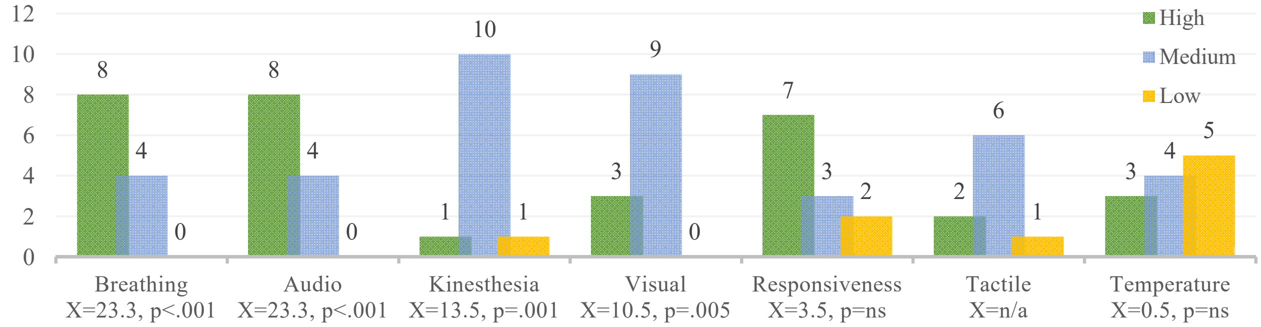

Figure 9: The distribution of participants across seven categories based on the immersion questionnaire. Below each category is the chi-square test ($X^2_{(2,N=12)}$) result.

bit too slow to go up...”, while P8 said that *“the movement was too enhanced.”* As people have slightly different breathing styles underwater, this might have caused them to react differently to the breathing dependent simulated motion. On the rating scale question of *‘how realistic was the up and down movement using your breath?’*, 8 participants rated high, and the remaining 4 rated neutral. The chi-squared test on the distribution of participants was significant ($X^2_{(2,N=12)} = 23.29$, $p<.001$).

Audio. In general, participants found the audio to be realistic. When asked to rate how well could they identify sounds, 8 participants rated high, and 4 rated neutral ($X^2_{(2,N=12)} = 23.29$, $p<.001$). In the open-ended interview, 4 participants found the breathing bubble sounds to be very realistic, and 2 liked the sounds of whales and sharks.

Kinesthesia. Kinesthesia was the lowest rated feature of the system. In the immersion questionnaire, 1 participant rated high, 10 rated medium, and 1 rated low on average for all the rating questions on Kinesthesia ($X^2_{(2,N=12)} = 13.50$, $p=.001$). In the open-ended interview, a majority of the participants (8) found the physical support system uncomfortable. Of the 8, 3 participants found it distracting that they had to maintain balance on the torso support, 4 participants found it hard to support their neck while lying down and trying to look up and ahead, while 1 found the leg bands *“too elastic”* (P4).

There were also three broad comments on movement. First, participants mentioned that using hand swim movements felt unnatural as they do not correspond with actual hand movements used while diving (4). Since the hand movement visuals are closely connected to Kinesthesia, we believe that also caused participants to rate Visuals low despite several of them liking the graphically depicted marine life and ocean floor vegetation, air bubbles and general underwater lighting and atmospherics (described below).

Second, as mentioned by 4 participants, turning left and right was a problem. We had only implemented lateral movement and not full body turning. Additionally, using left hand motion for turning left instead of right and vice versa was the opposite of what a diver would do in real life:

> *“The side movement, I had to remember to move [my hands] inwards. Normally I would move them outwards, for diving.”* (P12)

Third, some participants wanted complete 6DOF motion support (6). This would allow them to duck dive and swim downwards into holes and caverns (2), or move left and right with their legs and torso, instead of their hands (4):

> *“If you're a diver, your hands are always close. What can happen is to use your right leg to move left and your left leg to move right. Usually, in the real world it is a full movement. You move your torso and legs. If I want to turn right, I just move my core.” (P6)*

We also received some positive comments on Kinesthesia. People liked the forward motion in water using their legs (2), the large up/down movements using their hands (2), buoyancy from the inflatable cushion in the torso support (2), and how the elastic bands supported their swim position (1). For example, P2 said: *“The torso part felt like it moved in a way that was realistic to diving or being in the water.”*

Visual. System visuals were not found to be very realistic. The average distribution of participants in the immersion questionnaire for visual realism was 3 for high and 9 for medium ($X^2_{(2,N=12)} = 10.50$, $p=.005$). In the open-ended interview, a majority of participants (10) had issues with the virtual representation of their hands. Some did not like the arm graphics in general (4), while others had problems with the arm movement (6).

On the positive side, 8 participants felt spatially present due to underwater visual features: bubbles (3), topography (1), kelp (2), and fish (2).

System Responsiveness. Participants were asked about the delay experienced between their physical actions and expected outcomes in VR. Two people did not experience any lag, while one found *“quite a delay” (P4).* Responding to two delay related rating questions, 7 participants rated low, 3 rated medium, and 2 rated high on average. The chi-square test on the distribution of participants was not significant ($X^2_{(2,N=12)} = 3.50$, $p=ns$). In real life diving, people experience a delayed reaction time with movements underwater. We believe this knowledge may have caused a majority of the participants to ignore the noticeable lag in the visual rendering (~100 ms); as P9 explained, *“almost none [delay]. You expect it underwater.”* This is one reason why diving simulation may differ from other VR sport simulators which require a faster response time.

Tactile. Tactile was rated high=2, medium=6, low=1 (3 did not respond). Three participants did not find the experience of grabbing and manipulating objects to be smooth. We believe this was caused due to the jitter in the rendering of the crab motion—as is also observed in the recorded video—rather than issues in the physical feedback provided by the inflatable ball. Two participants remarked that the idea of touching objects underwater was not environment friendly. The chi-square test on the distribution of participants was not performed due to limited numbers.

Temperature. Contrary to our expectations, temperature simulation was not noticeable. When asked *'how well could you feel the change in temperature?'* participants were almost equally distributed across the ratings of high, medium and low with 3, 4 and 5 participants respectively ($X^2_{(2,N=12)} = 0.50$, $p=ns$). In the open-ended interview, out of those who commented on the temperature simulation (6), a majority of them (5) did not notice the temperature change as they were too busy moving around and exploring. This is also the case in real diving, as explained by participants:

> *"The cold sensation of gel pack felt real. Temperature was very good, very close to real diving, but since you're moving all the time, you don't feel it. You know, I don't notice when I am [real] diving too, unless it is really hot or cold." (P9)*

Summary. Breathing simulation was found to be the most realistic part of the simulator. Especially significant was our novel simulation of the user's body rising up and falling down with each breath. Participants found the underwater sounds realistic, and in general, did not notice any lag in the simulation. Kinesthesia was the least appreciated part of the system, due to comfort issues, the idea of using hand swimming gestures in a diving simulation, and a lack of 6DOF motion support. Participants liked the graphics (e.g. fish, plants, rocks), audio (e.g. the whale song, sound of bubbles), and the dimly lit underwater ambience. They had mixed reactions to the tactile interaction with marine life and most of them did not perceive the temperature simulation.

DISCUSSION

How did immersion affect presence?

As described in the study findings section, participants rated Spatial Presence and Involvement factors moderately high, while Realness (or Experienced Realism) was rated low. We discuss these factors with respect to our system.

Spatial Presence. Participants felt spatially present in our system. We believe the main factors that contributed to the spatial presence were visuals, audio and breathing. Participants specifically said that some underwater visuals made them feel like they were really scuba diving, that audio was immersive, and the ability to control moving up and down with breathing was very realistic.

Involvement. High rating for *involvement* suggests that participants were engaged in our simulator. One participant got so involved that they imagined a feature we did not implement: *"As I went deeper, it felt harder to breathe [due to increased pressure], just like in scuba diving. I don't know if that was in my head or it actually happened."* (P2). Some of the distracting elements reported by participants were: the inability to balance on the torso support (4), not being able to get used to the unnatural swim gestures for a diving simulator (4), noise from external conversations in the testing space (2), and unavoidable instructions from the user study conductor (4). For this last observation, in particular, P11 said: *"I was focusing attention on you too, in case you speak anything... That was distracting."* Instead of using headphones that permitted sound, all those four participants recommended using noise-canceling headphones connected with both the VR sounds, and a microphone for verbal instructions from the researcher during the study.

Experienced Realism. Limited and unrealistic movements, and an uncomfortable support system caused the *experienced realism* to be rated low during the study. Discomfort and inability to balance well on the torso support, not being able to turn the body around realistically, and moving with a swim gesture instead of holding hands closer to the body, as is common in real diving caused the participants to *behave* unnaturally in the simulator.

Future improvements

We asked the participants how they would change the current system to make it more immersive. In addition to changes in comfort level (6), motion support (6), and speed of up/down motion caused by breathing (3), three participants wanted real life scenes instead of animated graphics (*e.g.*, *"Why not real [graphics]? Like DiveIn360* [54]*")*. We think for a visual diving experience with no interactivity or motion, that would be a great alternative. Three participants wanted a nose clip to avoid breathing from nose in the simulator (*e.g. "Close the nose [with clip] so that people don't breathe in from nose"*), and 4 wanted additional dive equipment to be simulated, such as the buoyancy compensator and tank (2), wet suit (1), or a depth gauge (1):

> *"A lot of scuba diving is equipment - wearing a tank, inflate your BC. All of that should be incorporated. Right now, it's like a hookup. It has to be all the complete thing, because if it's not, then it's not real scuba diving and can't be used for instruction." (P8)*

We believe future diving simulators should have a comfortable and natural kinesthetic system that allows for complete 6DOF motion. They should incorporate realistic breathing, and potentially include real life underwater scenes and sounds based on the goals of the system. Contrary to some participants' opinion, we would advise not to simulate the surplus dive equipment to make the system convenient and simple to use. Use of tactile feedback for two-way interaction should be further investigated using more responsive, smooth and full-body haptic techniques such as [10,15].

General Insights From Our Work

Though we chose to simulate the specific activity of scuba diving, some of our learnings have wider applicability across general VR simulators. We learned that even for building a simulator, which implies replication of its real world counterpart (*e.g.,* flight simulators used for training), it is not necessary to replicate every single sensation to create an immersive simulation. For example, even though temperature change is an important element of scuba in the real world, the divers in our study mostly ignored it. From the user testing, we also learned that sometimes a literal translation of a physical action does not carry over very well into a VR simulation; *e.g.,* the hand gesture we used for propelling the user forward in virtual waters. All the elements in the simulator need not be replicas of their real world equivalents and as designers we can use some creative license while also keeping system usability and user comfort in mind.

Oculus Rift as a VR Tool

There were some issues with the Oculus Rift DK 2 that impacted the user experience. Participants reported feeling dizzy (2), hot (3), or felt the Rift was too heavy (2) during the study. It also has a limited field-of-view (110°), and low resolution (640x800 per eye) which negatively impacted the experience of at least two participants. On the other hand, Oculus Rift can be thought of analogous to a scuba diving mask (3) which helped make the simulator more immersive:

> *"It felt like a diving mask… For any other sport, like tennis, it would be weird [to use Rift]. But for diving, there's a nice analogy." (P9)*

> *"As I was experiencing the simulator, it reminded me of things like sometimes the [scuba] mask doesn't fit well, I was scared the water would go in. It's pretty natural analogy between mask and the headset [Rift]." (P3)*

Limitations

First, our results are inferential due to low participant population, but future work would consider a larger sample. Second, conversations happening in the testing space, and instructions from the researcher during the study negatively impacted the experience of at least four participants. Future VR studies evaluating presence should use noise-canceling headphones for audio, and include a microphone for any verbal instructions. Third, several studies indicate that measuring presence with questionnaire is reductive, and that comparing the user's behavior in the virtual and real worlds would yield a more accurate result [8,20,22]. Time limitations forced us to conduct a lab study, but future work should test behavioral presence. Fourth, people's perception in VR is often affected by their own life experiences. Our results are based on user self-reports of their experience in our simulator. In order to avoid experiential bias, future systems should incorporate automated collection of body movement and other relevant data for comparative analysis. This also would help mitigate the novelty effect of experiencing a new technology like VR. In our study however, we did not observe novelty bias as the results were same across participants who had previously experienced VR (5) and those who had not (7).

CONCLUSION

We have presented the design and implementation of a virtual reality scuba diving simulator. Compared to available VR diving simulators that mostly include visual and auditory simulations, our system is more immersive as it incorporates a range of senses, namely, kinesthetic sense (proprioception), temperature (thermoception), tactioception (tactile) and balance (equilibrioception). The qualitative user study with 12 experienced scuba divers demonstrated that while our system has the characteristics to make the users *feel* like they are diving, the implementation of some elements could be changed for higher immersion. Future applications include a scuba training system, exploratory adventures in uncharted territories, and educational experiences, that can, for example, teach how to identify fish, or create awareness about environmental damage to oceans by incorporating visuals from real life.

ACKNOWLEDGMENTS

We thank Dr. Llyr ap Cenydd of Bangor University, UK for the Oculus Rift app code, and MIT students and staff Cornelle King, Harpreet Sareen, Damien Martin and Udayan Umapathi for their help with the project. The work was supported by the MIT Council of Arts Grant.

REFERENCES

1. Sinauer Associates. Where Is the World's Biological Diversity Found? http://sinauer.com/media/wysiwyg/samples/PrimackEssentials5e_Ch03.pdf
2. Blum, L., Broll, W., and Müller, S. Augmented reality under water. *SIGGRAPH 2009,* ACM Press (2009), 1–1.
3. Braun, V. and Clarke, V. Using thematic analysis in psychology. *Qualitative Research in Psychology,* 2008.
4. Ocean Rift. http://ocean-rift.com
5. Cheng, L.P., Lühne, P., Lopes, P., Sterz, C. and Baudisch, P. Haptic turk. In *Proc. CHI 2014*.
6. Fels, S., Kinoshita, Y., et al. Swimming across the Pacific: a VR swimming interface. *IEEE Computer Graphics and Applications 25*,1 (2005): 24–31.
7. Fröhlich, T. The virtual oceanarium. *Communications of the ACM 43*, 7 (2000): 94–101.
8. Heeter, C. Being There: The Subjective Experience of Presence. *Presence: Teleoperators and Virtual Environments 1*, 2 (1992): 262–271.
9. Levett, D.Z.H., and Millar, I.L. Bubble trouble: a review of diving physiology and disease. *Postgraduate Medical Journal 84*, 997 (2008): 571–578.
10. Lindeman, R.W., Page, R., Yanagida, Y., and Sibert, J.L. Towards full-body haptic feedback. *Virtual reality software and technology 2004*, ACM Press (2004), 146.
11. Livingstone, S.D., Nolan, R.W. and Cattroll, S.W. Heat loss caused by immersing the hands in water. *Aviation, space, and environmental medicine 60*, 12 (1989): 1166–71.
12. Nichols, S., Haldane, C. and Wilson, J.R. Measurement of presence and its consequences in virtual environments. *International Journal of Human-Computer Studies 52*, 3 (2000): 471–491.
13. Ong, S.K. and Nee., A.Y.C. Virtual and Augmented

Reality Applications in Manufacturing. *Springer Science & Business Media,* 2013.

14. Rheiner, M. Birdly an attempt to fly. *SIGGRAPH 2014 Emerging Technologies*.
15. Roston, G.P., and Peurach, T. A whole body kinesthetic display device for virtual reality applications. *Robotics and Automation*, IEEE (1997), 3006–3011.
16. Satava, R.M. Virtual reality surgical simulator. *Surgical Endoscopy 7*, 3 (1993): 203–205.
17. Schroeder, R. Being There Together and the Future of Connected Presence. *Presence: Teleoperators and Virtual Environments 15*, 4 (2006): 438–454.
18. Schubert, T., Friedmann, F. and Regenbrecht, H. The Experience of Presence: Factor Analytic Insights. *Presence: Teleoperators and Virtual Environments 10*, 3 (2001): 266–281.
19. Schultheis, M.T. and Rizzo, A.A. The application of virtual reality technology in rehabilitation. *Rehabilitation Psychology 46*, 3 (2001): 296-311.
20. Slater, M. and Wilbur, S. A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. *Presence: Teleoperators and Virtual Environments 6*, 6 (1997): 603–616.
21. Steuer, J. Defining Virtual Reality: Dimensions Determining Telepresence. *Journal of Communication 42*, 4 (1992): 73–93.
22. Strickland, D. A virtual reality application with autistic children. *Presence: Teleoperators & Virtual Environments 5*, 3 (1997): 319–329.
23. Takala, T., Savioja, L. and Lokki, T. Swimming in a Virtual Aquarium. https://mediatech.aalto.fi/~ktlokki/Publs/va_2005.pdf
24. Witmer, B.G. and Singer, M.J. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments 7*, 3 (2006): 225–240.
25. Report on decompression illness and diving fatalities. https://diversalertnetwork.org/medical/report/2005DCIReport.pdf
26. World of Diving. http://divegame.net
27. Depth Hunter 2. http://store.steampowered.com/app/248530/
28. Infinite Scuba. https://infinitescuba.com
29. AquaCAVE: Augmented Swimming Environment with Immersive Surround-Screen Virtual Reality. http://lab.rekimoto.org/
30. Challenges of Sensing in Water. http://elasmo-research.org/education/white_shark/challenges.htm
31. Temperature of Ocean Water. http://windows2universe.org
32. 80/20 Inc. https://www.8020.net
33. Peltier Thermo-Electric Cooler - Adafruit Industries. http://adafruit.com
34. Unity 5. https://unity3d.com/5
35. Skeletal Tracking | Leap Motion. https://developer.leapmotion.com
36. API Reference - Leap Motion Java SDK v2.3 documentation. https://developer.leapmotion.com
37. Low-Pressure-Drop Mass Flow Meter SFM3000 - Sensirion. http://sensirion.com
38. BÖHM Wireless Bluetooth Headphones - Amazon. http://amazon.com
39. NeoSport Wetsuits Premium Glove 3mm - Amazon. http://amazon.com
40. Adafruit Industries. https://adafruit.com
41. Arduino Board - Due. https://arduino.cc/en/Main/ArduinoBoardDue
42. JBtek 4 Channel DC 5V Relay Module - Amazon. http://amazon.com
43. 2-Way Control Valves - Pneumadyne. http://pneumadyne.com
44. 1515-LS-Black - 80/20 Inc. https://8020.net/1515-ls-black.html
45. 1530-LS-Black - 80/20 Inc. https://8020.net/1530-ls-black.html
46. 40-2759-Black - 80/20 Inc. https://8020.net/40-2759-black.html
47. Black Mountain Resistance Band Set - Amazon. http://amazon.com
48. Rainbow Reusable Flexible Gel Ice Pack - Amazon. http://amazon.com
49. Buoy Modern Office Chairs & Seating - Steelcase Store. http://store.steelcase.com/seating/lounge/buoy
50. Cando 30-1870B Blue Inflatable Vestibular Disc, 300 lbs Weight Capacity. Retrieved January 19, 2016 from http://amazon.com/Cando-30-1870B-Inflatable-Vestibular-Diameter/dp/B003YRBLXQ/ref=sr_1_19?ie=UTF8&qid=1453163090&sr=8-19&keywords=inflatable+cushion
51. Champion Sports Ultra Quiet Air Compressor Inflator - Amazon. http://amazon.com
52. Zeny® 3,5CFM Single-Stage Rotary Vane Vacuum Pump - Amazon. Retrieved January 19, 2016 from http://amazon.com/Zeny%C2%AE- http://amazon.com
53. igroup presence questionnaire (IPQ) overview - igroup.org project consortium. http://igroup.org/pq/ipq/index.php
54. Dive In 360. http://divein360.com/
55. Seidel, R.J. and Chatelier, P.R. Virtual Reality, Training's Future?: Perspectives on Virtual Reality and Related Emerging Technologies. *Springer Science & Business Media,* 2013.