Article

Using Virtual Reality in Sea Level Rise Planning and Community Engagement—An Overview

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Abstract: As coastal communities around the globe contend with the impacts of climate change including coastal hazards such as sea level rise and more frequent coastal storms, educating stakeholders and the general public has become essential in order to adapt to and mitigate these risks. Communicating SLR and other coastal risks is not a simple task. First, SLR is a phenomenon that is abstract as it is physically distant from many people; second, the rise of the sea is a slow and temporally distant process which makes this issue psychologically distant from our everyday life. Virtual reality (VR) simulations may offer a way to overcome some of these challenges, enabling users to learn key principles related to climate change and coastal risks in an immersive, interactive, and safe learning environment. This article first presents the literature on environmental issues communication and engagement; second, it introduces VR technology evolution and expands the discussion on VR application for environmental literacy. We then provide an account of how three coastal communities have used VR experiences developed by multidisciplinary teams—including residents—to support communication and community outreach focused on SLR and discuss their implications.

Keywords: virtual reality; climate change; sea level rise; community outreach; environmental literacy; Santa Cruz; Long Beach; Turner Station; coastal adaptation

1. Introduction

It is estimated that 230 million people currently live in locations less than one meter above high tide, with 630 million people currently living in areas projected to be flooded annually by 2100 [1]. As coastal communities in the United States and around the globe contend with the impacts from climate change including coastal erosion, more frequent intense storms and sea-level rise (SLR) [1–4], educating stakeholders and the general public has become essential in order to adapt to and mitigate these risks.

However, communicating SLR-and other environmental issues—is not a simple task. First, SLR is a phenomenon that is abstract as it is physically distant from many people, given that 60% of people live more than 60 miles from the coast [5]. As they are not in daily contact with the ocean and may not realize how the coast and the ocean influence every aspect of human life, this issue is not of much concern to these people. As expressed by Longo and Clark "the ocean is commonly viewed as something far removed from human

society. In some way, it is deemed 'out of sight, out of mind" [6]. Second, the rise of the sea is a slow and temporally distant process which makes this issue psychologically distant from our everyday life [7]. Third, the general public presents limited understanding about earth and marine sciences [8], which makes it difficult to comprehend that the sea level is rising.

This article first presents the literature on environmental issues communication and engagement; second, it introduces VR technology evolution and expands the discussion on VR application for environmental literacy. We then provide an account of how three coastal communities have used VR experiences to support communication and community outreach focused on SLR and discuss their implications. The three VR experiences described in this article were developed by multidisciplinary teams including virtual reality researchers, climate scientists, city officials, community organizers, conservation practitioners, journalists, videogame developers, and digital artists. These VR experiences were funded by state agencies, non-profit organizations, local governments, and the private sector.

1.1. Communicating Environmental Issues

Focusing on personal connection, relevance and learners' agency has been argued to be more efficient [9,10], as direct experience of an environmental issue is more powerful than second-hand information [11]. Providing information alone is not enough to trigger behavioral or attitudinal change [12,13]. Experience not only affects how individuals learn about and perceive risks but also their behavioral responses. The "Experience-Perception Link" [14] research field investigates how experiencing the causes of environmental issues (such as extreme weather) influences individuals' attitude and behavior toward these issues. Researchers have shown a positive correlation between experiencing environmental issues and risk perception [15], attitudes [14] and behavior [16]. In their recent study, Bergquist and colleagues (2019) surveyed Floridians before and after they experienced hurricane Irma and suggested that "respondents expressed stronger negative emotions toward climate change, were more certain that the hurricane was caused by global warming, and were more willing to pay higher taxes after experiencing Irma" [17]. Since other scholars have not seen any positive change in environmental attitudes after experiencing extreme weather [17,18], Bergquist et al. (2019) postulated that experiencing extreme weather events might impact attitudes under certain conditions [17]. In other words, the framing of these experiences might have a key role to play. For example, in their study, Joireman et al. (2010) primed participants with words either neutral or related to heat before surveying them on their climate change belief and experience [19]. Participants primed with heat-related words were significantly more likely to have noticed signs of global warming and to believe in global warming.

Similarly, anchoring has also been suggested to impact climate change attitude. As defined by Teovanovic (2019), the "Anchoring effect refers to a systematic influence of initially presented numerical values on subsequent judgments of uncertain quantities, even when presented numbers are obviously arbitrary and therefore unambiguously irrelevant" [20]. Joireman and colleagues (2010) demonstrated that participants initially presented with high values in relation to global warming were more likely to believe that global warming was currently happening and more willing to pay to mitigate global warming compared to participants who were initially presented with lower values in relation to global warming [19].

The reviewed literature suggests that, while the experience of the environmental issue itself is critical, the context in which it takes place is also a key element if one wants to promote pro-environmental behavior and attitudes. In this way, how the experience is scaffolded is essential and needs to be better understood. Moreover, projections about the future impacts of SLR can be a difficult thing for people to picture in their minds and is consequently a difficult problem for communities to prioritize over more tangible and immediate ones.

Virtual reality (VR) simulations may provide an alternative, enabling users to learn key principles related to climate change and coastal risks in an interactive and safe learning environment. This idea is well aligned with research that argued that a suite of interactive 'management flight simulators' should be developed for policy makers and the general public to support the risk communication process [21]. VR experiences can simulate some impacts from climate change that are not immediate, such as coastal flooding—a concept that cannot be learned by real experience (opposed to virtual) without putting people at risk.

Recent research has shown that VR increases knowledge and preparation for natural disasters, when compared with traditional communication methods (i.e., videos or printed materials) [22]. An early study demonstrated that subjects visualizing flooding in three dimensional images declared a higher intent to purchase flood insurance and to evacuate from at-risk areas, when compared with subjects visualizing videos or slides [23].

A recent study in Florida found that participants that viewed two dimensional static maps showing SLR projections were less likely to say they believed climate change was happening and that it was causing more frequent storms, than participants that had not seen the static maps [24]. Regardless of partisan affiliation, participants expressed skepticism about the idea that SLR would have an impact in their property values after seeing the flood maps [24]. The authors attribute this counterintuitive result to partisan affiliation and personal interests, proposing that: "When partisans are exposed to new information that contradicts their existing beliefs, they may process any new information with an underlying goal or motivation to maintain their initial view or uphold their partisan group identity" [24]. Another recent study proposed that the use of compelling images such as animated maps in conjunction with effective textual frames can weaken science politicization, restoring the impact of textual frameworks [25]. While understanding how the use of VR may reduce science politicization is beyond the scope of this article, this is an area that warrants future research and is encouraged by these emerging findings.

1.2. VR Technology—A Brief History

The 20th century experienced three platform waves: personal computers, internet, and mobile devices [26]. However, even after the third wave, we were still confined to two dimensional devices. It was not until the fourth platform wave that we were able to break free from two dimensional screens.

That is when the fourth digital wave comes in. In the fourth digital wave, extended realities (XR) were introduced with three new key technologies: (i) virtual reality (VR)—the physical world is replaced with a fully virtual world, where everything is rendered by a graphical device; (ii) augmented reality (AR)—a digital layer is rendered on top of our physical world, augmenting it; (iii) mixed reality (MR)—which combines VR and AR presenting an experience that builds the digital layer on top of the physical world but in a more immersive way [27].

XR technologies became popular in the 2010s. However, humans were already dreaming about VR in 1832, when Sir Charles Wheatstone invented the stereoscope viewer [28], a device capable of combining two two-dimensional images, creating a stereoscopic image resulting in the illusion of a three-dimensional image. Over a century later, the first concept of virtual reality was finally defined in the science fiction book "Pygmalion's Spectables", in 1935 [29]. It describes exactly how virtual reality works today, although incorporating smell and taste into XR applications is still a tremendous challenge [30].

"I photograph the story in a liquid with light-sensitive chromates. I build up a complex solution—do you see? I add taste chemically and sound electrically. And when the story is recorded, then I put the solution in my spectacle—my movie projector. I electrolyze the solution, break it down; the older chromates go first, and out comes the story, sight, sound, smell, taste—all!" [29].

One of the first multisensory machines, known as the Sensorama, was created in 1962 by Morton Heilig. The Sensorama could display three-dimensional stereoscopic films as

well as trigger wind and aromas [31]. In 1961, Philco Corporation launched the Headsight, considered to be one the first head-mounted displays (HMD). Shortly after, in 1965, Ivan Sutherland launched The Ultimate Display, which he described as "a looking glass into a mathematical wonderland" [32]. These head-mounted displays were expensive and bulky [33].

It was not until the late 1980s that virtual reality technology took its next leap when the National Aeronautics and Space Administration (NASA) took an interest in the technology to train astronauts [34]. In 1989, VPL, founded by Jaron Lanier, launched the HMD EyePhone [35]. Shortly after, in 1990, NASA launched the HMD VIEW [36], but these two HMD were very limited in performance. Until very recently, processing power and costs were the great limitations preventing the technology from being more widely used [37]. In 1995, Nintendo, a Japanese videogame company, launched the Virtual Boy, an HMD considered one of the greatest failures in VR industry [38]. One of the reasons for the failure was the large number of users experiencing motion sickness because of the bad performance.

After the third digital wave (mobile devices) HMD started to receive attention again. In 2013, the Oculus Rift HMD was released [39]. In 2014, the company was acquired by Facebook Technologies, LLC for $2.3 billion [40]. That same year, Google LLC launched their versions of HMD, the Cardboard [41]. In 2016, Sony Corporation launched the PlayStation VR©, an add-on to the popular PlayStation 4 game console [42]. In 2018, HTC Corporation launched the HTC VIVE HMD [43] (Figure 1).
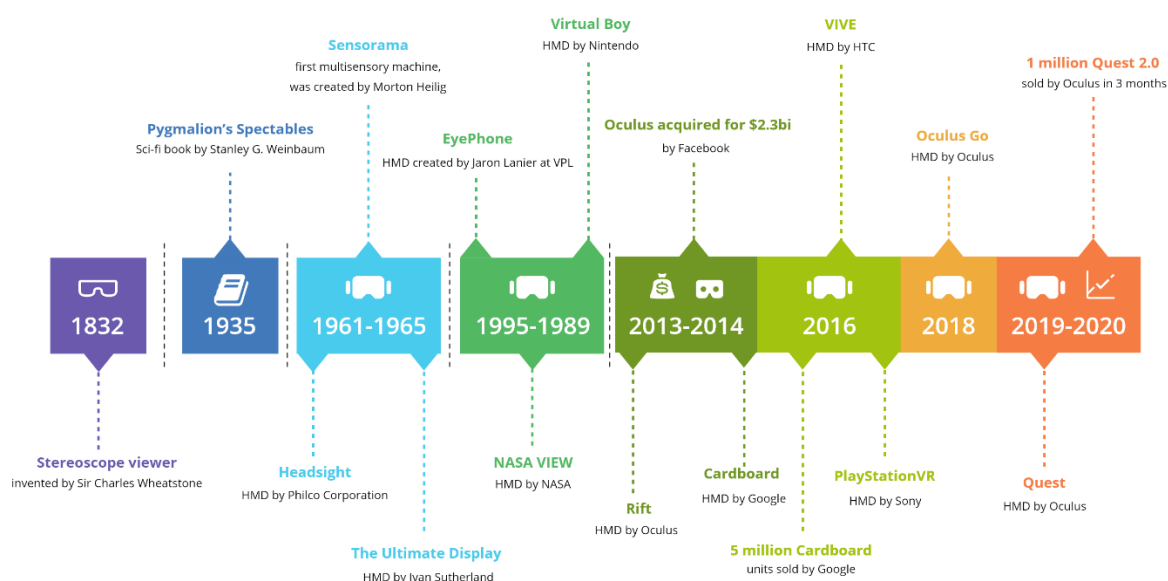

Figure 1. VR Technology timeline.

Most modern standalone VR HMDs with electronic components have at least two key motion sensors: an accelerometer that can measure at which speed the hardware is moving, and a gyroscope that can measure orientation in the x, y, and z directions [44]. Combining data from these two sensors, the device can track the direction the user is looking at, allowing three degrees of freedom (3DoF), which means the headset can track head movement in all directions [45]. While 3DoF is not the best way to experience virtual reality, it provides a pretty good feeling that you are in a virtual world.

The Google Cardboard, a simple do-it-yourself project literally cut from cardboard, with two attached lenses that work in conjunction with most modern mobile devices, proved that virtual reality can be achieved at a very low additional cost. Other 3DoF devices are not very expensive and are not PC dependent, which lowers costs even more. The Cardboard was a big success with over 5 million copies sold by January 2016 [46]. One

of its main uses was in education. With a program called Google Expeditions, for example, we can bring the whole world to users without requiring them to travel.

However, mobile devices were not built for VR and have serious limitations including: (i) their graphic hardware is limited; (ii) all images must be rendered twice; (iii) they overheat after a few minutes. Regardless of its limitations, mobile VR is cheap and accessible as mobile phones are ubiquitous. To improve the quality of the experience without adding much cost to it, Oculus released the Oculus Go HMD, a 3DoF standalone device. The Oculus Go had a mobile engine behind the scenes but it was developed for VR and provided a reasonable experience.

Over time, HMDs have received major upgrades, including spatial room awareness, which allowed users to finally move around in the virtual environment, resulting in an experience with six degrees of freedom (6DoF). In 6DoF, it is not only possible to track where the user is looking at, but also track where they are in the room, providing an entirely new perspective, and enhancing the way we perceive virtual reality [45]. The PlayStation VR and the VIVE HMDs represented an important leap forward as they introduced spatial awareness (6DoF). They were the first devices with spatial awareness and required external cameras and sensors to track the user location and multiple cables attached to the HMD [47].

Recent HMDs are cheaper, wireless, and introduced the concept of inside-out tracking, which reduces hardware costs and improves the user experience, since now the users do not need to position additional sensors [47,48]. These were two main barriers to the wide-spread use of VR. At this time, the recently released Oculus Quest version 2 had sold over 1 million units in just three months [49].

Looking forward, we expect VR and AR to continue to change how we consume content in the form of more portable devices that are more integrated with our day-to-day activities. Exploratory and innovative tools are being developed to support education, training, sales, transportation and more [50] and are likely to become mainstream as hardware costs decline and the technology continues to advance.

1.3. Environmental Literacy

1.3.1. The Need for an Environmentally Literate Population

In order to participate in the debate about and the actions toward marine environmental issues such as SLR, citizens need to be ocean literate. While the primary meaning of the concept of literacy solely refers to the ability to read and write, this concept has evolved through time to include the ability to understand a text and be able to make sense of and use it in the world for relevant purposes [51]. More recently, UNESCO expanded the concept of literacy by stating that, "Literacy involves a continuum of learning in enabling individuals to achieve his or her goals, develop his or her knowledge and potential, and participate fully in community and wider society" [52]. Various types of literacy, such as science literacy, digital literacy, or environmental literacy, point to skills that are essential in our time and that include but go beyond reading and writing in the classical sense [53]. Cava and colleagues (2005) defined ocean literacy as an understanding of the ocean's influence on us and our influence on the ocean. Elaborating on this understanding of interdependencies, the authors define an ocean-literate person as someone who understands the essential principles and fundamental concepts about the functioning of the ocean, is able to communicate about the ocean in meaningful ways and is able to make informed and responsible decisions regarding the ocean and its resources. Since SLR is forecast to have economic, social, health and environmental ramifications, it is essential that citizens and decision-makers are well-versed in this environmental issue. Dealing with SLR and adapting to it will require awareness and engagement from every citizen, from coastal community members to the government. The engagement of every citizen is essential for the successful implementation of mitigation plans. That is, it is necessary to start from understanding and move toward the behavioral change and action of entire groups—near and far from the coast.

When it comes to engagement with climate change issues, there are three main elements: understanding, emotion, and action [54]. In order to be able to engage the community, citizens, and decision-makers, it is essential that they receive proper information and understand the causes and consequences of SLR regionally and globally. In addition, it is important that they feel emotionally connected to this issue, so that they move forward to action. Having firsthand experience with marine life and coastal environments has been shown to increase people's understanding and emotional responses, which can lead to greater support for nature conservation work [55]. Hence, the challenge is to promote an emotional connection with the ocean among people living inland. Finally, after understanding and being emotionally connected to the SLR issue, opportunities to participate in action, mitigation and adaptation are essential to garner support for decision-makers in coastal areas.

1.3.2. VR for Environmental Literacy

Through the use of a head-mounted display, hand controllers, stereoscopic sound, and haptic feedback, immersive virtual reality (VR) provides a vivid first-person experience in a three-dimensional virtual environment augmented with multisensory feedback. Virtual experiences have become more immersive as technological development increases the sensory information provided, allowing users to feel more in touch with the virtual experiences. Bailenson argues that VR is best suited when it simulates experiences that are otherwise dangerous, impossible, counterproductive or expensive [56]. VR has shown encouraging results tapping into understanding, emotions, and behavior, as well as communication and planning to address environmental issues.

Understanding. Markowitz et al. (2018) explored the efficacy of VR for teaching about ocean acidification [57]. The VR activity was first implemented in school as part of a teaching unit running over several weeks. The students embodied a coral avatar and experienced the ill effects of ocean acidification on other species and on their own avatar. The students' knowledge about the topic increased after participating in the VR activity. A similar experiment was run, but this time, half of the participants saw themselves as a coral, while the other half embodied a scuba diver. Both groups presented a significant knowledge gain between pre- and post-test, but there was no difference between the two conditions, indicating that, in this case, the nature of the avatar did not influence the knowledge gain [57]. A third experiment focused on the impact of participants' movement. Forty-three participating college students were randomly assigned to two motion conditions (swimming with remote control or with their physical body). While the motion condition did not influence the knowledge gain, it showed a post hoc correlation between the knowledge gain and the distance traveled underwater. This suggested that visual and physical exploration while in VR led to a greater knowledge gain [57].

Emotions. Hsu et al. (2018) investigated the effects of exaggerated feedback to trigger an affective response in VR experience about water conservation [58]. The authors focused on the effect of exaggerated feedback intensifying the negative consequences of water consumption and/or environmental damage in order to emphasize affective responses. A total of 165 participants played a VR game simulating water consumption effects. Participants were assigned to one of the four exaggerated feedback conditions: negative impact on the environment (present or absent), and negative impact on resources (present or absent). Participants in the "negative impact on resources" condition demonstrated higher short-term behavior intention to reduce water use than participants in the "negative impact on the environment" condition [58]. Regarding the long-term effects of exaggerated feedback, participants in the "negative impact on the environment" condition showed a greater improvement in individual attitude and behavior intention than participants in the other conditions [58]. These results indicated that providing exaggerated feedback of water usage on the environment (i.e., degradation of the environment) elicited the highest levels of affective response and pro-environmental disposition [58].

Behavior. Ahn et al. (2014) investigated the impact of an embodied experience in VR on environmental behavior related to paper consumption [59]. Forty-seven college students were first informed about paper consumption and its impact on deforestation before being randomly assigned to one of two experimental conditions. Half of the participants put on the VR headset and virtually stood in a forest in front of a large tree while holding a chainsaw. They were prompted to begin moving a haptic joystick to cut down the tree. After two minutes of sawing, the tree would fall down, and the forest would become suddenly quiet. The participants in the second condition read a detailed description of the tree-cutting activity and were prompted to create a vivid picture in their minds. Ahn and colleagues (2014) revealed that after experiencing how to cut a tree in the VR condition, participants used significantly fewer napkins to dry spilled water than participants who read a passage about cutting a tree [59].

Chirico et al. (2020) also placed individuals in a virtual natural environment in order to communicate an environmental problem [60]. They investigated how VR could contribute to mitigating the plastic pollution issue while participants were transported to a garden during the spring season. While at first the natural environment was pristine, the plastic consumption of the participants along with the global plastic consumption was visualized onto the natural environment. Each participant was randomly assigned to one of the three different kinds of visualizations. In the concrete condition, the amount of plastic was represented by a pile of bottles of plastics piling up in front of the participant. In the numeric condition, the plastic consumption appeared as a number superposed to the natural environment. Finally, in the mixed condition, both the numbers and the bottles were visible at the same time. The authors measured a wide range of variables such as attitudes toward the environment and plastic waste, and behavioral intention toward plastic. The results showed a significant effect of the mixed condition compared to the numerical condition. The awareness of risks related to the use of plastic was significantly greater in the mixed and concrete condition than in the numerical one. The awareness of risk related to plastic use was also greater in the mixed condition than in the numerical condition.

Communication. When it comes to risk communication, immersive media has been shown to be more effective than non-immersive ones [61]. A study using immersive 360° videos investigated this media effect on individuals' psychological distance, personal relevance, perceived risk, and behavior related to environmental issues [61]. They found that increased immersion was beneficial to communicate the severity of environmental risks and enhance pro-environmental behavior. On the other hand, they demonstrated that increased immersion was detrimental for environmental issues that were already considered as proximal.

McLean, Taladay, and Dong (2020) have also addressed the use of VR to communicate the impacts of SLR in Hawai'i, a state threatened by this environmental issue [62]. They designed a VR experience based on sea level rise data provided by the National Oceanic and Atmospheric Administration (NOAA). Their aim was to create an entertaining but impactful experience to be used as a communication tool. Their paper describes the technical development of the tool but does not provide information about its implementation and impact on the audience.

Planning. Focusing on visualizations and how it could support risk communication and decision-making, Jude and colleagues (2015) developed a VR simulation about coastal change and adaptation strategies [63]. After interviewing coastal management organizations about the VR simulation, they found that it was important to facilitate the communication between the coastal management organizations, stakeholders and the public. They suggested that future visualization methods should include: (i) long-term coastal change based on scientific projections, (ii) geomorphological changes, and (iii) coastal-scale visualizations. An experimental research using this VR simulation showed that VR could improve economic valuation of changes on the landscape, when compared to traditional media [63].

In this context, the objective of this study is twofold: First, the development of three VR experiences by a multidisciplinary team aiming at enhancing environmental literacy, particularly sea level rise-related issues; second, the use of those experiences for communicating about sea level rise in collaboration with three coastal communities.

2. Materials and Methods

In this section, first, we describe the key components of the VR experiences and highlight what they have in common, as well as unique features developed for each location as the technical framework evolved during the last two years. Next, we provide an overview of how a typical project is executed, highlighting the main project phases: planning, data acquisition, creation and testing, and experience rollout.

2.1. Sea-Level Rise Explorer VR Description

These VR experiences were developed in the *Sea Level Rise Explorer Framework*© developed by Virtual Planet Technologies, a climate communication startup located in Santa Cruz, CA [64]. Each VR experience features a customized three-dimensional virtual space designed to reflect each location's characteristic and 'look and feel' and include a step-by-step guided experience. The VR experiences are available in English and Spanish (except in the case of Turner Station, only available in English).

Each of these VR experiences address SLR from the point of view of three different U.S.-based coastal communities impacted by SLR, namely, Turner Station in Maryland, Santa Cruz in California, and Long Beach in California. The virtual environments were designed after consulting locals and reviewing local cultural materials, so they accurately represent each community. Images from each experience are shown on Figure 2.

| (a) | (b) | (c) |

Figure 2. Three dimensional virtual rooms; (**a**) Turner Station; (**b**) Santa Cruz, (**c**) Long Beach.

In the Turner Station VR experience, developed in 2019 [65], the virtual space was modeled after the lunchroom at the treasured Turner Station Senior Center (Figure 2a) and is centrally featured in the experience. Through a glass door, users look out to the park, and on the left wall they see pictures of noteworthy residents from the community and interact with photographs to hear their stories. In the Santa Cruz VR experience, developed in 2020 [66], users are transported to a beach house with surf boards, pictures of the city, and windows that overlook a 360° panoramic view of the famous Santa Cruz wharf (Figure 2b). Finally, in the Long Beach VR experience, developed in 2020 [67], users are immersed in a beach house modelled and decorated after the local homes at the Alamitos Peninsula, the main location featured in the experience (Figure 2c). In the virtual rooms, users can see additional two-dimensional information on a large screen that is also used as an interactive user interface. Photos of the local coastal areas are hanging on the virtual walls and users can interact with the various features in the experiences using a virtual laser pointer.

At the beginning of each VR experience, users are oriented through a brief tutorial learning how to interact with the environment. The three main actions users can perform in the experience consist of (i) clicking on flashing targets to move to the next step, and (ii) clicking on icons to activate and deactivate features such as displaying coastal erosion and coastal adaptation, and (iii) clicking and dragging a circle over a sliding bar to simulate

the impacts of ocean waters rising. During initial testing stages, the development team found that many users, especially those not familiar with VR, did not realize they could move their heads to explore the immersive 360-degree environment. To prevent this lack of interaction with the environment, an extra step was introduced to the tutorial, encouraging users to look around to explore the virtual environment around them.

After the tutorial, users have about 30 s to explore the space on their own and just look around to get used to the VR space and observe images and objects related to each community culture. We found that in previous pilot versions that did not include this quiet time (i.e., the narration started sooner), most users could not recall what they had heard as they were distracted by the novelty of VR. After users spend some time looking around the virtual room, a 1-min two-dimensional introductory video starts on a virtual screen in the VR environment. The first half of the video shows the planet Earth spinning and the atmosphere warming while a narrator describes how climate change is causing sea water to heat and expand, and glaciers and ice sheets to melt, both driving sea levels to rise. The second half of the video is unique to each location and shows aerial images with special highlights from each location. The introductory video is not present in the Turner Station experience as it was introduced more recently.

After the introductory video, a three-dimensional model of a coastal location is displayed on top of the desk in front of the user and a new user interface appears on the virtual canvas behind the desk. Users can interact with a sliding bar to simulate sea levels rising and can interact with various buttons to display coastal erosion, the impact of extreme storms, and to visualize potential adaptation solutions, as seen in Figure 3. These same features are also available during a second scene, where users are transported to an aerial view where they can see each location while floating from a virtual blimp 120 m above the ground.

Figure 3. View of the Long Beach VR virtual room with three-dimensional model of Alamitos Park showing the impacts of 24 cm of projected SLR in the low-lowing area.

2.2. VR Creation Steps

2.2.1. Planning

During the planning phase, the key objectives of each experience and main audiences were identified. These VR experiences were designed to provide a novel and compelling tool to increase awareness on SLR. They have been customized to each location to allow users to identify with that location, aiming to increase their connection with the issue being pictured. The VR experiences were used in several community outreach events at these locations to start communications with residents about SLR and other coastal impacts (i.e., coastal storms and coastal erosion).

Once the objectives and audiences were defined, the next step was the creation of a visual storyboard. The storyboard contained concept images of each step of the experience including a welcome screen, brief tutorial, introduction video, the virtual room, and the aerial views, based on Google Earth images of the relevant locations. In parallel with the storyboard, the narration script was developed and eventually translated to Spanish. Once the storyboard was completed, all the aerial image needs were identified. The drone flight plans were documented and when needed, flight permits were requested.

In this phase, to support the realistic renderings used to build the VR experience, relevant coastal hazards were selected along with science-based projections. Typically, these include flooding models, tidal information including king tides (the highest astronomical tides of the year), historical and projected coastal erosion, as well as all coastal adaptation concepts. The data sources used were the National Oceanic and Atmospheric Administration SLR data [68,69], the Coastal Storm Modeling System (CoSMoS) developed by the United States Geological Survey (USGS) [70], The Nature Conservancy Coastal Resilience mapping portal [71], and higher resolution models developed by local consultants when available.

2.2.2. Data Acquisition

During the data acquisition phase, all drone flights were executed at the portrayed sites. Various kinds of aerial images were required to develop the VR experiences: still photographs were used in photogrammetry to generate three-dimensional models, additional videos were used in the experience, and photographs and videos were used in communication materials. The main drone used in these projects was the DJI Phantom 4 pro version 2, which has a one-inch optical sensor that can take 20-megapixel images. The three-dimensional models used in these VR experiences were produced from around 800 aerial shots. In the case of the larger model of the Long Beach Peninsula, it used more than 3500 images, taken over the course of five days (Figure 4).

2.2.3. Creation and Testing

The main steps in the implementation phase included photogrammetry, artistic work, and technical development. During photogrammetry, two dimensional aerial views were processed into three dimensional models. These models were simplified into lower resolution models that could be added into VR without overtaxing the HMD's limited processing power. Additionally, 360° aerial panoramas were created. Then, the artistic renderings were created to realistically replicate the coastal hazards selected during the planning phase for each location. The renderings were either overlaid to the 360° images or the 3D models and integrated to the experience using Unity, a cross-platform mostly used to develop video games [72]. During this phase, the experiences were tested in several platforms and all bugs were fixed. Once the experiences were validated by the project partners, they moved on to the rollout phase.
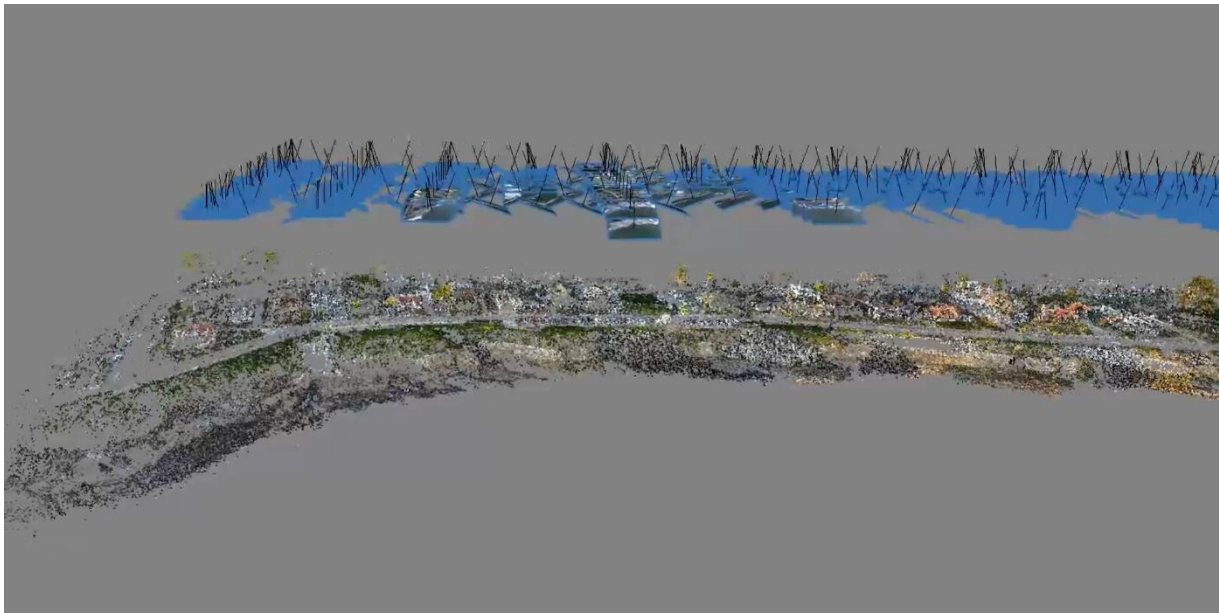
Figure 4. Simulation of drone data acquisition and photogrammetry steps. The blue squares represent each photograph taken by the drone as it flew over the area of interest (Santa Cruz, CA, in this case). The point cloud, generated by photogrammetry techniques, is shown in the lower part of the image, and the black lines show the camera angles and estimated drone position.

2.2.4. Rollout

During the rollout phase, the applications were published on various app stores including Oculus Go, App store, Play Store, as well as online. The experiences are almost identical across platforms, but each platform has a few unique features. Mobile versions include a 360° view option that uses the devices' gyroscopes to allow users to move their phones as if they were cameras or a window into each virtual environment. As users change the orientation of their phones, it auto rotates their screen. On mobile devices, users can also click and drag the 360° images to rotate their views. In the web-based application, they can perform the same action by clicking and dragging images with the mouse.

2.3. Coastal Hazards Models Selection

The physical hazards data selected for these experiences are based on results of commonly used, peer-reviewed models with the highest spatial resolution available at the time. Once each hazard model was chosen (e.g., CoSMoS), specific model scenarios were selected for each experience (e.g., 0.8 m of SLR). The model selection process was based on recommendations from recent publications and state guidance (e.g., [3,73]), and in consultation with local experts. The participation of local experts was a key part of the process as they ensured the models and scenarios included in each VR experience were consistent across ongoing community efforts and plans to address SLR.

It is important to note that the physical hazards included in these VR experiences (i.e., coastal flooding from SLR and storms, and coastal erosion) were based on the best available models for each location. We simply represented the results of the selected models in the visualizations included in the VR experiences. The term 'simulation' is used in this article as a reference to the VR experiences only, as they are often designed as simulations of reality in constructed immersive environments; in this context, the term 'simulation' does not refer to hazard model simulations.

The SLR models used in Turner Station, MD are from NOAA's Sea Level Rise Viewer. Flooding projections included in the VR experience range from 0.3 m (1 ft) to 1.83 m (6 ft), in 0.3 m (1 ft) increments. For specific model considerations and limitations, please consult reference [74]. Coastal hazards represented in the Santa Cruz VR experience include

king tides, a combination of 0.73 m (2.4 ft) of SLR with an extreme storm event (100-year storm), and projected coastal erosion by the year 2100. The flooding projections used were developed during a study conducted by a consulting firm (ESA) for the Monterey Bay area [75,76]. The coastal erosion projections used were prepared by a local consulting firm for a recent coastal planning report published by The city of Santa Cruz [77]. Coastal hazards represented in the Long Beach VR experience were developed by the USGS's CoSMoS models and include combinations of SLR scenarios ranging from 0.24 m (0.8 ft) to 1.49 m (5.9 ft) with or without an extreme storm (100-year storm) [70]. For a more in-depth analysis of SLR model methods and limitations in California, please refer to the Sea The Future tool developed by the California State Coastal Conservancy [78].

It is also important to note that natural hazards alone are not the best way to quantify risks to coastal communities. Such risks are better defined by complex interactions between physical hazards and the vulnerability of the communities affected by these hazards [79], which were not included in these experiences but should be considered in future VR experiences with similar objectives as the ones described herein. Finally, it is important to note that all models have limitations, and these VR experiences were developed as communication tools to start informed conversations; they were not designed to support site-specific decisions including permitting.

3. Case Studies—A Tale of Three Coastal Cities

Turner Station, MD; Santa Cruz, CA; and Long Beach, CA are three very different coastal cities that have historically faced coastal hazards likely to become worse with climate change. In this section, we describe how these three communities embraced VR as a tool to support outreach in their planning efforts.

Turner Station is a historic African American community located just outside of Baltimore. Due to the constant wet and soggy lawn, kids can barely play on the baseball fields at Fleming Park, a treasured community park [80]. In the surrounding neighborhood, a combination of precipitation, high tides and storm surges occasionally results in sea water flooding the streets through the storm drainage system designed to keep the local streets from flooding [80]. With climate change and SLR, the flooding frequency in this neighborhood is expected to increase [68]. Turner Station is located in the mid-Atlantic region where, by 2100, almost one million houses are projected to be vulnerable to three feet of SLR, the low end of most SLR projections for the region [3].

Nearly 2900 miles across the country, in Santa Cruz, CA, severe coastal erosion is causing parts of the pedestrian pathway and bike lane along the iconic West Cliff drive to fall into the ocean [77]. During strong El Niño years, when sea levels in California can be almost 30 cm higher than normal, a couple of local coastal roads just outside the city limits can remain flooded for weeks, disrupting the local traffic and damaging infrastructure [77,81]. In the city of Santa Cruz alone, with an estimated population of roughly 65,000 people in 2020 [82], more than $1 billion of property and infrastructure will be at risk if the existing coastal armoring is not replaced by 2060. A recent study found that without extensive human intervention, 67% of all sand beaches in California could disappear by 2100, due to a combination of SLR and coastal erosion [83].

Three hundred miles south of Santa Cruz, residents of the Long Beach Peninsula in Los Angeles county are looking for solutions to protect hundreds of homes from flooding resulting from coastal storms. In 2018, Long Beach residents watched the waves from hurricane Sergio break through the 10 foot-tall sand berms that the city builds and maintains year-round, and overtop the short seawall built around the entire peninsula, the last defense against ocean waters. During that event, emergency responders erected a plywood wall behind the short seawall and deployed sandbags to protect coastal homes [84].

These three locations are a few examples of thousands of coastal communities across the globe facing coastal hazards that are being exacerbated by climate change [1]. VR simulations may offer a way to help citizens overcome some of these challenges, enabling users to learn key principles related to climate change and coastal risks in an immersive and

interactive learning environment—this has evoked sometimes visceral emotions [85]. This concept is well aligned with a body of research that assesses the efficacy of various traditional communications modalities as compared to more realistic or experiential modalities such as VR, as discussed before.

3.1. Turner Station, MD

Turner Station is a vibrant, venerable, and historic community dating back to the 1880s [86]. The community blossomed as an enclave of black employees of the Bethlehem Steel Company, who were barred from living in other nearby neighborhoods by segregation laws, moved to this region, building small cabins for their families [86]. Ultimately, residents built a wealthy and distinguished community that prided itself on education and self-sufficiency with its array of community-run businesses [86]. Turner Station became a vibrant and thriving community that is home to many notable residents including an NAACP president and former congressman, an astronaut, musicians, artists, and many more [87].

Over time, Turner Station's shores have been eroded by wave action and rising seas and the local water quality has been degraded by a long history of industrial shoreline activity within the community and across the region. Turner Station's predominantly black community is active, organized and working to preserve its historic foundation and revitalize its shores to increase community resilience to current and future challenges.

3.1.1. Project Background

The Nature Conservancy (TNC), a global environmental nonprofit present in 72 countries and territories with more than a million members and over 400 scientists [88], is working with communities on climate adaptation in many ways all over the world, encouraging investments in nature-based solutions to reduce the impact of flooding. In Maryland, TNC is working to empower coastal communities and habitats with the innovative frameworks they need to adapt to the increasing pace of coastal transformation caused by climate change.

TNC partnered with Virtual Planet Technologies (VPT) to develop a VR experience that would bring to life the projected extent and impacts of SLR to Fleming Park (Figure 5b–d). The goal of the project was to use VR to start a conversation with the community about the projected impacts of SLR and to work together in the development of adaptation strategies, identifying where and how nature-based solutions can reduce current and future risk and impacts. The initial project was launched as the Turner Station community, working with Baltimore County and a team of partners, gained momentum in planning a multimillion-dollar shoreline revitalization and restoration project at Fleming Park—a treasured coastal asset within the Turner Station community. The goal of the project was to use the visualization as a launching point for a partnership wherein community-led resilience planning would ultimately lead to a more robust consideration of SLR adaptation in the shoreline park revitalization project design. This aimed at increasing the lifetime of this significant investment of public capital, as well as the longevity and resilience of the park itself for the community's enjoyment.

VR was used in this project for two main reasons. First, we expected it would cause a great impact due to its novelty. Second, we expected the use of VR would result in increased engagement from the local community and decision-makers, when compared with traditional communication methods such as two-dimensional images (see the Introduction Section for the literature review about VR use and prosocial behavior change and natural disaster preparedness).
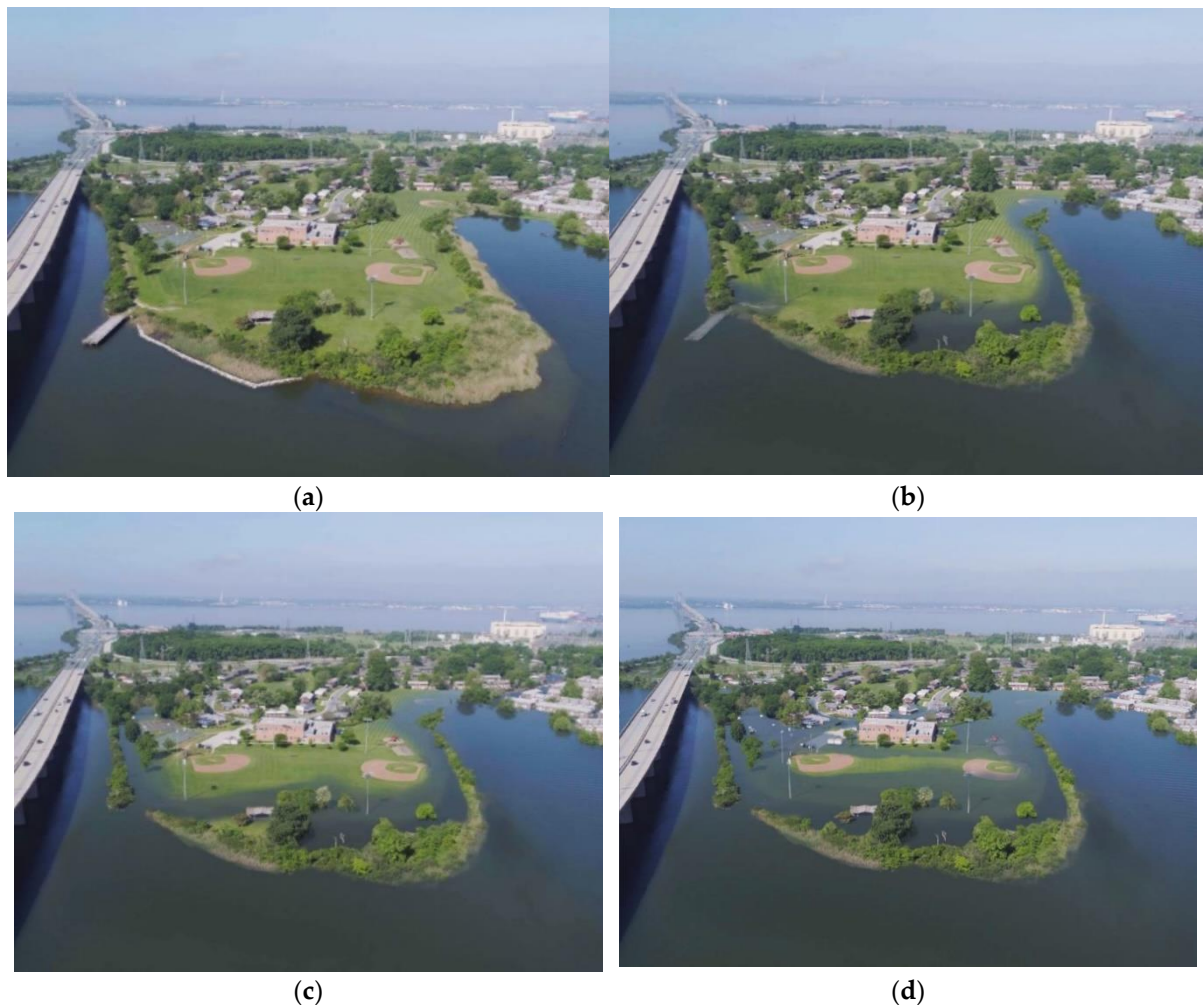
Figure 5. 360° aerial views of Fleming Park View, MD; (**a**) high tide, summer of 2019; (**b**) 2 ft of SLR; (**c**) 4 ft of SLR; (**d**) 6 ft of SLR; (based on SLR projections from NOAA SLR Viewer [69]).

3.1.2. VR Application

The development of the visualizations had some unanticipated positive effects. Upon viewing the first beta version of the visualizations, the project team and partners immediately recognized that the original geographic scope—focusing on Fleming park—only told a fraction of the story of the current and projected impacts to the entire Turner Station community. In order to have a robust, community-led dialogue about adaptation, the scope of the visualization would need to be expanded.

The partners opted to conduct a soft rollout of the original tool at the community's annual Community Resource Information Fair in Autumn 2019 with the acknowledgement that it was only the first phase, and that there were future plans under development to expand the geographic scope to the entire community, as well as to visualize potential adaptation solutions.

The soft rollout consisted of a booth at the fair staffed by The Nature Conservancy's coastal resilience team, a Turner Station Conservation Team Inc. community representative, and a technological expert at Virtual Planet, along with a representative from the consulting firm leading the effort to revitalize the park. Approximately 30 community members tested out the technology and spoke informally to the facilitators about their immediate impressions of the visualizations. The rollout was covered by numerous high-profile national news venues, with reporters capturing some of the community members' reactions to the technology itself, as well as the information being presented [80,85]. The media attention

assisted in securing additional donor interest and financial support for the expansion of the project.

In November 2019, the VR experience was displayed at the Maryland Port Administration's annual Dredged Material Management Program Meeting. While viewership was not recorded, a long line of people queued up to experience the virtual SLR demonstration.

3.1.3. Next Steps

Funding has been secured to develop a new version of the VR experience in a two-phased approach. The first phase would include the visualization of flooding risk for the entire community (beyond just Fleming Park). The second phase would include community-identified, coastal engineer-approved, nature-based solutions to reduce flood risks. The goals of these two phases are: (i) to help community members and decision-makers to better visualize the impacts of climate change and SLR, and (ii) choose phased adaptation options amongst a suite of potential solutions. Ideally, this will help the community identify some near-term solutions to reduce current risk while launching a longer-term adaptation planning effort as sea levels continue to rise.

3.2. City of Santa Cruz, CA

The city of Santa Cruz is located on the central coast of California, slightly south of the San Francisco Bay and Silicon Valley, nestled between the Santa Cruz mountain range and the Pacific Ocean. A laid-back beach town of about 65,000 residents receiving an average of 262 days of sun per year, the city hosts 3 to 4 million visitors a year, making tourism and recreation primary economic drivers [89]. Santa Cruz has a diverse coastline including beach and recreational resources, transportation and utility infrastructure, higher-end residential development, the iconic Santa Cruz Boardwalk and less-advantaged residential and commercial areas in the flood plain of the San Lorenzo River.

3.2.1. Project Background

The city of Santa Cruz has a long history of strong environmental action and is a leader in coastal climate change resiliency planning. In 2011, the city developed the first Local Hazard Mitigation Plan (LHMP) in California to include SLR projections and adaptation strategies. In 2012, the city completed a climate change vulnerability assessment [90] that included distinct measures to bolster resiliency. In 2016, Santa Cruz prepared a coastal climate change analysis incorporated into the Climate Adaptation Plan adopted in 2018, projecting the spatial and temporal extent of erosion, SLR and coastal storm flooding [91] and refined resiliency actions to 44 distinct measures. A major finding was that by the end of the century, there are an estimated \$1B in infrastructure and property assets projected to be exposed and vulnerable to the sea level [91].

Following the adoption of the city's revised LHMP [92] and Climate Adaptation Plan Update in 2018, two new projects were initiated under the city's Resilient Coast Santa Cruz Initiative. Commencing at the start of 2019 and concluding in the spring of 2021, the two projects are the West Cliff Drive Adaptation and Management Plan and the Local Coastal Program (LCP) Amendment to include policies for beach access and protection.

West Cliff Drive is a nearly three-mile multi-modal scenic corridor running three quarters of the length of the city's coastline. The West Cliff Drive Management Plan had long been called out for development in the city's LCP [93] (City of Santa Cruz, 1994) to address how this city asset and the protective structures of its coastline will be managed and adapted over time. However, funding and staffing had stalled previous efforts. A grant from the California Department of Transportation enabled the city to gain the expertise and capacity to build on the momentum and relationships it had developed through the LHMP and Climate Adaptation Plan Update, both adopted in 2018. As the engagement for this project was coordinated with the complementary LCP amendment project funded by the Coastal Commission, the project benefitted from a dedicated engagement consultant at no charge to the CalTrans project, resulting in two well-coordinated projects.

Building on the city's award winning Climate Adaptation Plan Update engagement, the Resilient Coast team designed a living engagement plan for the Resilient Coast initiative that resulted in over 1500 conversations with community members and stakeholders at over 50 meetings and events to date [94]. The team employed a number of engagement strategies, featuring the use of VR, to enhance engagement accessibility and creativity, which became crucially important as the team pivoted to online engagement with the advent of COVID-19. Promotion for each major engagement event was extensive and materials were provided in English and Spanish. A Google analytics report indicates that visits to the city's Resilient Coast webpage increased 10-fold in the transition from in-person to virtual engagement when compared with previous months [95].

3.2.2. VR Application

The goal of the VR experience uses in the Resilient Coast engagement were (i) to provide a novel and compelling tool to increase awareness on SLR and (ii) to gain community feedback on coastal adaptation preferences. The VR experience supporting this initiative were phase-developed and their English and Spanish versions can be accessed online, through VR HMDs and mobile phone apps. The city, in collaboration with Virtual Planet Technologies LLC, adapted an existing VR application proof-of-concept into the VR SLR Explorer. The experience runs in VR headsets to provide hyper-realistic visuals. See Figure 6 for sample images illustrating current conditions, King Tides, and SLR projections [94].

| (**a**) | (**b**) | (**c**) |

Figure 6. Cropped views from the 360° aerial images of Main Beach, Santa Cruz, CA included in the SLR Explorer Santa Cruz; (**a**) summer of 2019; (**b**) king tides, 2019; (**c**) 0.73 m of SLR combined with 100-year storm.

In a community event using VR SLR Explorer, users were guided through the experience, learned about coastal issues and solutions (Figure 7) to address SLR, and answered survey questions on preferences and awareness-building.

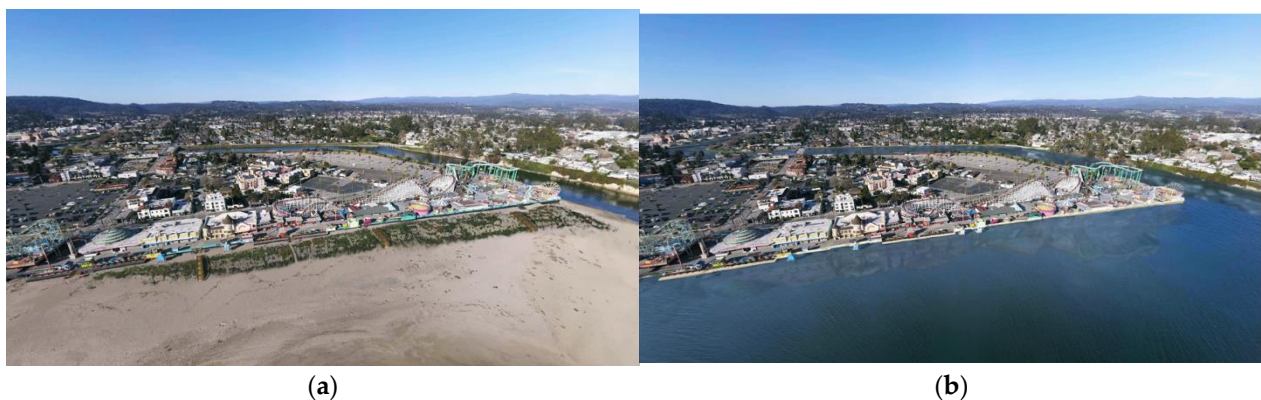| (**a**) | (**b**) |

Figure 7. Cropped views from the 360° aerial images of Main Beach, Santa Cruz, CA included in the SLR Explorer Santa Cruz; (**a**) conceptual images of a Living Shoreline adaptation approach; (**b**) conceptual image of a seawall as an adaptation approach. As the beach cannot migrate inland due to seawall, with SLR, the beach would eventually drown.

Community members had VR headsets available to view the 360 images depicting projected shoreline change at the city of Santa Cruz's iconic beaches and West Cliff Drive (Figures 6 and 7). The project also leveraged grant funding from the American Geophysicist's Union and California Coastal Commission to build adaptation solution designs into the beta VR application and embed a survey to assess user awareness of SLR impacts and preferences on adaptation options.

The VR SLR Explorer application was adapted for use at Santa Cruz Public Library branches. This project has enabled a broader reach and depth of engagement with the community, supporting the Resilient Coast Santa Cruz Initiative. At a three-month exhibit at the Main Library branch, over 200 library patrons viscerally experienced coastal changes and learned about coastal issues and solutions using VR technology. Other successful VR demo events included the opening of the Felton library branch, Santa Cruz Museum of Natural History, Santa Cruz Emergency Preparedness Event, Alliance of Regional Climate Collaboratives for Adaptation meeting, and Resilient Coast Community Open House [95] (Figure 8).

Figure 8. Two women trying the Sea Level Rise Explorer Santa Cruz, VR at an SLR open-house event organized by the city (photography by Juliano Calil).

After experiencing the SLR Explorer VR experience at the Santa Cruz library, participants reported that "Having the control of the ocean rising makes it visceral", "3D experience is much more powerful than photo models", and "I was relatively aware already but having point-of-view visuals is very impactful".

The VR SLR Explorer Santa Cruz was made available in both English and Spanish as a mobile phone and online application, available on both the Apple and Android app stores. The app was also available for download on Oculus Go HMD. By February 2021, nearly 2500 users had installed these applications across these three platforms combined [96–98] and nearly 1000 people tried them at various outreach events hosted at these communities.

The VR, mobile, and online versions of the Santa Cruz experience included a three-question survey that all users that completed the experience could select to answer. These three questions were designed to better understand users' preferences and awareness after viewing the experience's content. The three questions included in the survey were:

1. To what extent do you agree with the following statement related to coastal management for Mitchell's Cove?
2. To what degree do you agree with the following statement regarding coastal management for Main Beach?
3. Rate how your awareness of sea level rise has changed as a result of this experience.

The preliminary results show that nearly 63% of users (74 out of 118) reported a significant or very significant change in their awareness of SLR after participating in the

VR experience. More than 46% of users (69 out of 149) agreed that adding a seawall as a near-term solution for Mitchell's Cove is the best approach for Santa Cruz and the community. Nearly 65% of users (79 out of 123) agreed to some extent that adding more sand and vegetated dunes in the near-term and adding a taller seawall in the long-term is the best plan to protect Main Beach in Santa Cruz.

3.2.3. Next Steps

Survey data from the VR, mobile, and online experiences continue to be tracked and used to inform future planning around SLR in Santa Cruz. Moreover, the city is currently applying for grants to secure additional funds to expand VR application in two main areas: visualization of adaptation pathways at the city's sandy beaches and communicating potential risks from inland flooding in the downtown area. Finally, a new study comparing the use of VR vs. traditional SLR planning tools, such as two-dimensional maps, is being prepared. The study will compare learning rates, knowledge retention, and adaptation preferences, based on delivery medium.

3.3. City of Long Beach, CA

Communities across California are developing climate vulnerability assessments and community adaptation plans to identify ways to reduce risks in the future. A contentious adaptation option is managed retreat, defined as "the purposeful, coordinated movement of people and assets out of harm's way" [99]. In California, various communities are deciding how, if at all, to build managed retreat into their plans for long-term resilience. In some communities, the consideration of managed retreat in local plans collapsed even before the community could begin to evaluate it as an adaptation strategy.

TNC in California teamed up with the Long Beach Aquarium of the Pacific (AOP) to shape a community dialogue around SLR adaptation and the role of managed retreat in one of California's largest coastal cities, Long Beach. The goal of these dialogues was to find ways of engaging residents that empower them to participate in the design of future communities. Virtual Planet Technologies and TNC California developed a VR experience with input from both stakeholders and the community to visualize SLR impacts and potential solutions for Long Beach. This VR experience served as a tool to catalyze community discussions about current and future risk and options for long-term resilience, including controversial topics like managed retreat.

Long Beach, California sits on the southern edge of Los Angeles County, about 20 miles from the heart of the city of Los Angeles. A coastal city, Long Beach is home to approximately 500,000 residents, with a popular waterfront and the second busiest container port in the United States, second only to its immediate neighbor, the Port of Los Angeles. Two major rivers, the Los Angeles and San Gabriel rivers, discharge to the Pacific Ocean in Long Beach and are heavily altered and channelized. Once extensive systems of coastal wetlands, much of the coastal area has since been filled and developed. Oil and gas were discovered in the 1920s, driving the development and industry at the time, a legacy that is still apparent to this day.

King tides and coastal storms are already causing flooding in Long Beach. Near-term SLR projections will exacerbate these challenges and lead to more frequent impacts to the community. According to a vulnerability assessment conducted by the city of Long Beach, approximately 1.3 million square feet of buildings in Long Beach could be exposed to annual king tides by 2030. Approximately half of these buildings are residential (624,100 square feet) and half are commercial (689,600 square feet) [100]. In the long-term, there will be permanent inundation of some areas, especially in the coastal communities of Alamitos Bay in Long Beach, the focus of this case study. Alamitos Bay consists of the communities of Belmont Shore, Naples island and the Long Beach Peninsula. Once a large system of wetlands, Alamitos Bay is now home to about 40,000 people.

The city of Long Beach is developing the city's first Climate Action and Adaptation Plan to help the community reduce greenhouse gas emissions and prepare for the impacts

of climate change, while also improving the quality of life and enhancing the economic vitality of Long Beach [100] (city of Long Beach, 2020). In the plan, the city is considering strategies to adapt to the potential impacts from SLR and storms. AOP is a close collaborating partner with the city of Long Beach, producing a first climate vulnerability study for Long Beach [101] (AOP 2015), convening experts, and assisting with outreach and public education.

3.3.1. Project Background

TNC has been working to ensure a more resilient coastline since 2007, recognizing the critical role for nature to prepare coastal communities for more intense and frequent flooding from climate-driven SLR. Nature can provide a buffer for communities, but adequate space is needed to provide this protection. In California and lots of other places around the country, communities have been built and continue to build right up to or in coastal hazard zones. This is particularly true along the urban southern California coastline. To protect communities and regain this critical buffer, it may mean keeping and perhaps moving things out of harm's way to restore nature's protection. In June 2019, TNC in California formally partnered with the Federal Emergency Management Agency (FEMA) Region IX to develop ways for communities to protect themselves from natural disasters using natural infrastructure solutions and to better understand the role of managed retreat to realize community-scale risk-reduction. This effort focuses on testing communication strategies and approaches that would motivate a community to plan for retreat from SLR vulnerable houses before major disaster losses are incurred and while there is still an opportunity to restore the natural coastal processes that could buffer more landward development. TNC presented to the commissioners of the California Coastal Commission in December 2019 to describe this effort and initial results and lessons learned that may be useful in other communities in California and the agency's approach to communicating about managed retreat.

Long Beach was identified as a potential case study because the city had already carried out a great deal of climate adaptation planning, and the issue of managed retreat was already being discussed in community forums. TNC sought out a trusted local partner who could help navigate the sensitivities of a community, in this case, AOP. AOP's President and CEO, Dr. Jerry Schubel, was already very active in the community on these questions and worked extensively with city officials and the planning department on evaluating vulnerabilities, bringing the best available science and information to bear, and engaging the community through forums sponsored by the aquarium. TNC and AOP teamed up to shape a community dialogue around SLR and pathways to a more resilient Long Beach, both in the near term and for future generations. The focus was to bring to bear innovative visualization tools, and different perspectives from the fields of design, economics, law, policy and communications to stimulate productive conversations on the role of managed retreat in adaptation and help the community envision the possibilities for a new Long Beach, resilient to its future climate reality. It was important for both organizations to establish and be transparent about their respective goals right from the beginning. Among the goals that were shared was stakeholder empathy—that we were seeking to, first and foremost, listen and hear from the community so we can better understand residents' concerns about the future of the area and hear community perspectives on potential scenarios to enhance resilience of the coastal area, including the possibility for managed retreat and the appropriate circumstances when that might come into play.

3.3.2. VR Application

The development and use of the VR experience were important components to the managed-retreat engagement project. Initial versions were shown to participants in project seminars and focus groups to both open the discussion on SLR and gain input along the way to improve the tool. TNC worked with Virtual Planet Technologies to develop the *Long Beach Sea Level Rise Explorer* to visualize SLR impacts and potential solutions for Long

Beach and help engage the public around these issues. The purpose of this VR experience was not to scare people but to create realistic understanding of the issue, and to show potential solutions.

Since 2007, TNC coastal resilience projects focused on working with climate scientists and stakeholders to develop and communicate about SLR models. They aim to assist local governments in planning and improve public awareness of the growing risks and challenges. Although SLR modeling continues to advance, the way planners and the public interact with and view the results tend to remain primarily through 2D maps or GIS platforms. While these types of maps can be effective for planning purposes, there is some indication that these are not very effective at raising awareness and generating support for adaptation actions with the general public [24,25].

TNC and AOP convened five events to date to increase SLR awareness. These events included three large public forums and two focus groups from October 2019 to March 2020, reaching approximately 300 people. At each event, the participants had an opportunity to interact with VR in some way. At the first large public seminar in October 2019, attendees were introduced to the project, to VR, and heard from a leading SLR expert. Dr. Juliano Calil gave a presentation on VR and early development of the tool for Long Beach [102]. Participants were also able to put on the VR goggles and see the initial aerial visualizations. Over 100 people attended the event, and it was live-streamed.

In November 2019, AOP and TNC co-hosted and co-facilitated the first listening session focus group with 18 residents from the vulnerable communities in Alamitos Bay to hear community concerns about SLR and their thoughts on potential solutions. During the listening session, every participant donned the VR headset and experienced an early version of the Long Beach visualization tool to provide input and reflections on the experience (Figure 9).

Figure 9. Residents of the Long Beach Peninsula in a hearing session at the Aquarium of the Pacific having a discussion on the experience of the Long Beach VR tool (photograph by Juliano Calil).

From a virtual blimp above Belmont Shore and Naples, participants dragged a cursor to visualize how different extents of SLR might inundate the coast (Figure 10). After each participant had a chance to view the experience, the group reconvened to share reflections and discuss the experience. A takeaway from this listening session was that VR made visible the impacts of SLR that were missing in 2D maps of SLR. Participants shared that the VR experience felt very realistic, and that it made more of an impact on them than seeing 2D maps on paper. Some noted surprise that storm surge and SLR might affect homes on the bayside on Ocean Boulevard, not just the ocean-front side of the peninsula.

(**a**)   (**b**)

Figure 10. Three-dimensional models as shown in the Sea Level Rise Explorer Long Beach (**a**) Long Beach Peninsula; (**b**) Alamitos Park.

Subsequent events focused on providing different perspectives on adaptation and hearing additional reactions and input on the VR. A team of design students from the ArtCenter College of Design in Pasadena, CA [103] presented on design concepts to reimagine this area. Another public seminar and focus group focused on engineering solutions and perspectives. After each event, the VR development team considered comments and input from attendees as further visualizations were developed and refined, and a script was developed. A final convening, now postponed due to the COVID-19 pandemic, will focus on discussion around legal, real estate and financing options that may enable managed retreat or long-term resilience. The COVID-19 pandemic presents other challenges to be able to share the VR experience and conduct outreach. The team is currently examining ways to ensure more safety once it is deemed safe to hold public convenings, including sanitizing devices and protocols for headsets, and developing a mobile application or other strategies to view the experience while physically distanced.

3.3.3. Next Steps

While this project has been impacted by the COVID-19 pandemic, halting both in-person outreach events, as well concerns related to the sharing of headsets, the team is preparing and evaluating options for the rollout of the VR experience, including safety protocols once it is deemed safe to resume in-person events and other strategies to share the VR while physically distanced.

Using VR for community engagement in this project leads to important social science questions around the effectiveness of the technology in engagement, how it might shape or change perspectives around climate change and different types of solutions. Using some of the VR experiences, the team is looking to develop a research project to better understand why and how people choose to adapt, and how communication and tools, such as more immersive visualizations, influence these decisions.

Finally, in partnership with Virtual Planet Technologies, TNC is developing two other VR experiences aimed at communicating about resilience strategies to partners, stakeholders, and the public. These include (1) a project looking at adaptation scenarios for Highway 1 and the railway through the coastal community of Moss Landing, CA, which also goes through the nationally important estuary of Elkhorn Slough, and (2) a project in partnership with the Paradise Recreation and Parks District to better understand what happened with the devastating Camp Fire and visualize whether open space around the community would help to reduce future risk.

4. Main Findings and Discussion

While the field of VR for environmental education is still in its infancy, previous studies have demonstrated the potential impact that experiencing environmental issues in VR can have on promoting behavioral and emotional changes toward the environment [58–60].

VR has also been argued to be a valuable tool to communicate environmental issues and risks, and to plan adaptation strategies [61–63]. The three VR experiences on SLR presented in this paper contribute to expanding the body of knowledge about how VR could be concretely implemented in order to trigger discussion, reflection, engagement and action toward SLR.

The experiences developed included some important features, such as long-term coastal change based on scientific projections and coastal-scale visualizations, reported as important when it comes to VR experiences for communicating and engaging with environmental issues [63]. Moreover, they were developed by multidisciplinary teams including virtual reality researchers, climate scientists, city officials, community organizers, conservation practitioners, journalists, videogame developers, digital artists, and residents from each community. All three applications include narrators that live in close proximity to the areas portrayed in the experiences.

The presence of team members that were actual residents of the project locations was a key success factor in both the development and use of the experiences. These members were able to provide local knowledge and guide the development and artistic work to make the VR environment more similar to the real locations. Local team members also ensured that the physical hazard models and scenarios selected were consistent with those included in community efforts and official plans (e.g., Local Hazard Mitigation Plans and Climate Action and Adaptation Plans). Moreover, local team members helped to promote events and facilitate discussions as they knew the community well and were highly engaged in SLR issues.

These VR experiences were used almost 1000 times at nearly 20 community events and were downloaded more than 2500 times across multiple platforms. Users of the VR experiences in the community events included residents, business owners, city staff, planners, elected officials, and even people experiencing homelessness. While these are not extremely high numbers, they represent a significant increase in the number of people engaging with SLR planning when compared with traditional processes. In the examples discussed herein, VR experiences were used to start hundreds of conversations about SLR impacts and adaptation. Users and project team members engaged in conversations about SLR models, the feasibility of adaptation options and their related costs and benefits, and the added benefits that could result from using nature-based solutions. This finding corroborated the study by Jude and colleagues (2015), in which a VR simulation enhanced communication between coastal management organizations, stakeholders, and the public [63].

The comments from participants after going through the SLR VR experiences indicate that these experiences enhanced SLR visualization. Participants reported that VR made it possible to visualize the impacts of SLR that were missing in viewing 2D maps. They also mentioned that the VR experience "felt very realistic, and that it made more of an impact than seeing 2D maps on paper". Other quotes related to enhanced visualization, obtained from an anonymous survey conducted at the Santa Cruz library, included: "I study sea level rise, but it really made it a reality", "It's not just words anymore", and "It drives 'real' reality home".

Additionally, when different content was presented in VR, the topics of conversation with users that had just tried the experiences seemed to change. When only SLR scenarios were shown, often the conversations led to questions around the models used and level of uncertainty and/or accuracy. Similarly, Jude and colleagues (2015) found that the application of VR in decision-making processes is often hindered by the technical outputs' specificities [63].

On the other hand, when solutions were shown, the conversations led to questions of feasibility and related costs. This finding corroborates the study by Judy and colleagues (2015), which showed that using VR visualizations could improve the economic valuation of changes on the landscape [63]. These effects, however, were not tested consistently, and more research in this area is needed.

Related to the above, participants reported that the VR experiences and the discussion to follow were "highlights" of the forums and community events. For example, one participant commented: "the casual, open forum helped make a difficult subject palatable". This indicates that compelling visuals and narrative framing can be effective in creating a space for dialogue.

The level of interest in the VR projects was noteworthy. VR is still novel enough that the mere presence of headsets at an event is enough to attract an audience. Most users that tried these experiences had never experienced VR before. In addition to community outreach applications, VR may also be a useful tool in fundraising and advocacy, bringing awareness to climate change issues and conservation work more broadly. To the best of our knowledge, the impact of VR on fundraising for environmental causes has not yet been the subject of a thorough investigation but constitutes an important component of sustainability.

In the three case studies presented here, users familiar with the locations portrayed in VR seemed to have stronger emotional reactions than users not familiar with them. This echoes Breves and Schramm's findings about the potential detrimental impact of immersiveness for issues that are already close to the users who might then consider it "too close for comfort" [61]. It would be interesting to further investigate the reaction from individuals living in these three locations compared to people who have not visited these locations. However, after understanding and being emotionally connected to the SLR issue, it is essential to promote action, mitigation, and adaptation strategies, particularly when it comes to coastal areas' decision-makers. It is not clear yet what the effects of these experiences will be in relation to these topics.

In Turner Station, the process of selecting areas and getting images to build realistic and immersive images resulted in the identification of more immediate issues for the community than initially thought. This is significant as the process of studying the area to develop the VR experience initiated an important dialog that would not be happening otherwise.

In Santa Cruz, preliminary survey results showed an increase in awareness of SLR after users participated in the experience. A more robust study would be needed to investigate understanding, knowledge retention, and long-term engagement resulting from these VR experiences.

The very low number of users that accessed the Spanish version of the Santa Cruz VR experience indicates that more work is required in the city to reach the Spanish-speaking community, one of the most vulnerable to SLR according to projections [91].

In the Long Beach project, the team found that developing renderings of long-term adaptation solutions that appropriately balanced realistic options and visionary concepts was very challenging, as stakeholders could not agree on the details of the final visuals nor the narration to accompany them. Jude and colleagues (2015) reported similar challenges when developing a VR experience to visualize coastal changes related to climate change [63]. The authors report coastal managers' concerns regarding the level of detail of the visuals presented and technology's limitations [63]. In the end, the long-term adaptation image showing the Long Beach Peninsula restored to its natural state as a wetland with the actual houses was removed from the published experience.

Limitations and Future Research

It is important to note that the case studies presented here were not designed to formally collect experimental data regarding the efficacy of VR vs. other methods of communication related to SLR. Except for the Santa Cruz VR experience, where very basic data were collected, the discussion was based on the teams' experiences and were listed as preliminary findings. The use of structured surveys and dedicated focus groups must be used to further explore and confirm or rebut our preliminary findings.

As environmental issues are an urgent matter that should be tackled collaboratively by communities, understanding the role that technologies can play in informing, educating, and fostering action among the public is essential and still under-studied for the moment.

We encourage future research to investigate the use of multiple communication media to evaluate what delivery methods and message frames are most effective at enhancing positive attitudes and preferences about adaptation to SLR including managed retreat. Furthermore, new research could also focus on communities that are still not aware—or not yet interested—in the local impacts of SLR.

Future studies should focus on important research questions that remain unanswered. One such question is related to the potential impact of information delivery method (i.e., printed materials, two-dimensional videos, or VR) on users' coping responses towards SLR. One approach to answer this question would be to build on the findings from Zaalberg and Midden (2013), which argued that, similarly to people with direct flooding experience, people that experience flood in more realistic simulations also show a higher intent to purchase flood insurance and to evacuate from at-risk areas [23]. A future study could test the hypothesis that visualizing SLR, coastal erosion, and flooding in VR would result in different coping responses (i.e., intent to evacuate from at-risk areas, purchase flood insurance or even permanently relocate from at-risk areas) when compared with traditional visualization methods (such as aerial photographs and maps). Tools such as the Sea Level Rise Explorer experiences discussed here could be used to support this research.

One proposed methodology to investigate these questions would be to conduct a study with three focus groups. First, participants of all three groups would watch the same introductory video about climate change and coastal impacts on a television screen. Next, each group would visualize SLR and coastal erosion impacts for the same location delivered in three different ways (all groups would listen to the same audio narration throughout the experiment). Group 1 would be presented with printed and audio materials only; group 2 would watch a film with high-definition aerial images on a television; and group 3 would participate in a VR experience with immersive images. After the experiment, all participants would answer the same questionnaire designed to measure emotional reactions, coping responses, and short-term knowledge retention. The objective of this proposed study would be to detect statistically significant variations in responses based on the information delivery method. Moreover, to increase rigor, future studies should include participants from large and diverse samples, follow those samples over time, and focus on behavioral measures, in addition to verbal and self-reported ones.

Finally, future studies related to the application of VR in SLR communication, engagement, and outreach should include social science components to investigate learning rates, short- and long-term knowledge retention, as well as to measure the impacts of framing the issues and solutions in different ways on future actions related to SLR engagement taken by participants.

5. Summary

This study contributes to expanding the body of knowledge about how VR could be used to trigger community discussion, reflection, engagement, and action toward SLR in real-life cases. The objective of this study is twofold: first, it presents three VR experiences developed by multidisciplinary teams aiming at enhancing environmental literacy, particularly SLR-related issues; second, those experiences are used to communicate about coastal hazards in collaboration with three coastal communities—Turner Station, MD; Santa Cruz, CA; and Long Beach, CA. These immersive and interactive experiences included important features, such as hyper-realistic visualizations of coastal changes, reported as critical to VR experiences that communicate environmental issues [63]. As of February 2021, nearly 1000 people tried these experiences at various outreach events—a significant increase in the number of people engaging with SLR planning when compared with traditional processes—and nearly 2500 users had installed these applications across multiple platforms. We expect these numbers to increase as we continue to promote and deploy these experiences at future events.

The main findings from these three case studies include: (i) in Santa Cruz, nearly 63% of users of VR at a library display (74 out of 118) reported a significant or very significant

change in their awareness of SLR after participating in the VR experience; (ii) immersive solutions can bring attention to new, and sometimes unexpected, topics. In Turner Station, the realistic 360° images developed resulted in an important dialog about community resilience that could not happen otherwise; (iii) including local team members was a critical success factor across these three projects. They added legitimacy and trust to the process, made sure the VR tools represented cultural aspects of each community properly, promoted the project and various community events, and ensured the physical hazard models and scenarios selected were consistent with those included in other community efforts; (iv) it is hard to build consensus around controversial topics. In Long Beach, a long-term adaptation image—showing the area restored to its natural state as a wetland—was ultimately removed from the final version of the published experience; (v) VR is still novel enough that the mere presence of headsets at an event is enough to attract an audience; (vi) users familiar with the locations portrayed in VR seemed to have stronger emotional reactions than users not familiar with them.

Finally, our findings corroborate the findings from Jude and colleagues (2015) that compelling visuals and narrative framing can be effective in creating a space for dialogue, and VR simulations enhance communication between coastal management organizations, stakeholders, and the public [63].

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