An Overview of Virtual Reality

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Abstract

Virtual Reality (VR) has existed for many years; however, it has only recently gained wide spread popularity and commercial use. This change comes from the innovations in head mounted displays (HMDs) and from the work of many software engineers making quality user experiences (UX). In this work we present a brief history, current research areas, and areas for improvement in virtual reality
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1 Introduction

As virtual reality (VR) continues to explode in popularity in corporate, education, entertainment, and research fields it is increasingly important to determine what VR can be used effectively for. It is well known that VR can increase a user's sense of immersion and presence in a virtual environment (VE). The benefits of VR come somewhat inherently from the medium itself, but also from a good user experience that finds it's roots in core human-computer interaction principles. This paper explains portions of why VR is important, and what research has been done on it's capabilities.

VR's explosion of growth has left a distinct impression on households in the U.S. Reports [9] show that 23 percent of households have used or owned a VR headset. This figure is heavily dependent on generation, with Silent Gen, Boomers, and Gen-X having 4, 6, and 18 percent having used or owned VR headsets respectively. Gen-Y and Gen-Z have 38 and 45 percent used or owned VR headsets respectively. Monthly active users for VR in 2019 was, reportedly, at 43.1 million people while in 2020 this number shot up to 52.1 million people. It is estimated that by 2030, 23 million jobs will use augmented reality and VR with healthcare, education, and blue-collar training being the most largely impacted.

The rest of this paper is structured as follows: In Section 2 we present a brief history of Virtual Reality. Section 3 outlines some of the current research areas, and Section 4 presents some areas for improvement.

2 A Brief History

While the current state of VR is dominated by commercially available head-mounted displays(HMDs) and various peripherals, an incredible amount of effort, time, resources, and

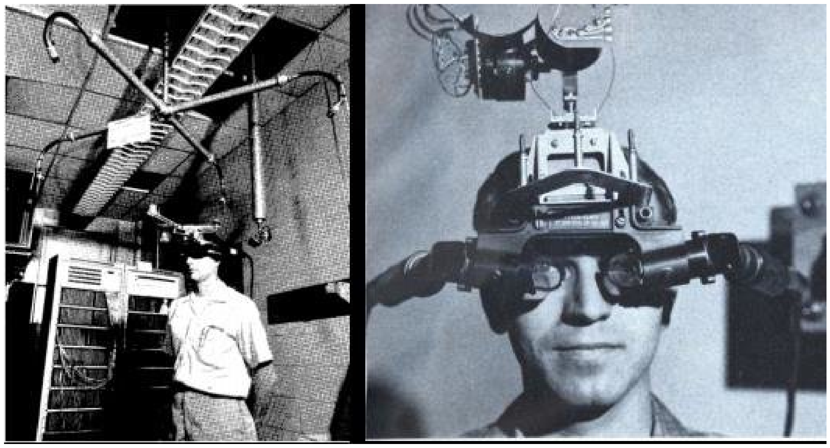

Figure 1: Ivan Sutherland's "Sword of Damocles" [24]

research had to be invested first. VR hasn't always predominantly used HMD's, but it is where VR started. In 1960, a cinematographer named Morton Helig would receive a US patent for an invention that could show images, emit sounds, and emit air currents that could vary in velocity, temperature, and odor. This was the first known HMD. This HMD was patented under the name of: "Stereoscopic-television apparatus for individual use" and is US patent number 2,955,156. Helig produced another notable advancement in VR called the Sensorama. The "Sensorama Simulator" was patented in 1962 and displayed 3D stereo video, stereo sound, aromas, wind, and had a seat that vibrated. These inventions mark the emergence of VR. Helig also wrote in his patent about the importance of this technology not only in a cinematographic sense, but also in: reducing hazardous situations/training for workers and the military; teaching devices to help education institutions; and multiplayer/social situations.

The next step in virtual reality quickly appeared after the Sensorama. This step came from Ivan Sutherland in the form of the "Sword of Damocles" seen in Figure 1. This invention was the first known HMD that could rotate the user's virtual field of view in tandem with how the user is physically moving their head. Dr. Sutherland's work and accomplishments are vast and could take quite a few pages of this paper. Dr. Sutherland is credited as a pioneer of computer graphics. He received the Turing award for his PhD thesis, "Sketchpad", which was the first of it's kind to use a complete graphical user interface (GUI). It also influenced, if not created, modern graphical user interfaces (GUIs) and object oriented programming. Dr. Sutherland went on to create many other notable technologies and influencing many other notable students. Dr. Sutherland created "Sword of Damocles" in 1968 with a few of his students at Harvard University. The most notable students are: Bob Sproull, the former director of Oracle Labs and current adjunct professor at the University of Massachusetts Amherst; and Danny Cohen who adopted the terminology "endianness" for computing and has been inducted into the Internet Hall of Fame. The Sword of Damocles itself actually only refers to the mechanical tracking system and not the head-mounted display itself. The Sword of Damocles is also considered the first augmented reality system as the system was somewhat translucent.

From 1970 to 1990 most VR was developed for medical simulations, flight simulations, and military training purposes. A few notable inventions did occur during this time, however. In 1979, Eric Howlett created the Large Expanse, Extra Perspective (LEEP) optical system. LEEP had a wide field of view and was added to NASA's Ames Research Center in 1985. Next, Jaron Lanier founded VPL Research in 1985 where VR peripherals were being created. The most notable VR peripherals from VPL Research were the “DataGlove” and “DataSuit”. The “DataGlove”, was one of the first examples of a wired glove, which acts as an input device for human-computer interaction. These gloves generally mirror what the user is doing with their hands in virtual environments, though there has been some use for wired gloves to have a robot mimic what a human wearing the gloves is doing. This “DataGlove” was then licensed to companies to make entertainment related technology, most notably the “Power Glove”, which was used by Nintendo in their Nintendo Entertainment System. It didn’t sell well and users notoriously had a hard time with it’s controls and imprecision. The “DataSuit”, utilizes the “DataGloves” as well as a full body suit that is filled with sensors that can measure the movement of arms, legs, and the torso.

The 1990’s saw some of the biggest changes to VR since it’s inception and the seminal systems by Dr. Sutherland. One of the largest issues with VR before this point was it’s cost. None of these headsets were available for commercial use and they were all generally geared towards large institutions like military, medicine, or academia. In 1991 Sega announced Sega VR, which never made it to release. That same year, Virtuality launched the first mass-produced multiplayer VR systems. These systems were created for the use in VR arcades and had a cost of $73,000 per system. While not quite commercially available to the end user, this shows a distinct increase in the use of VR for entertainment and non-industry use. Again in 1991, the next large step in VR was taking place in academia.

The Cave Automatic Virtual Environment (CAVE) was a PhD thesis created by Carolina Cruz-Neira [5]. Daniel J. Sandin, a professor emeritus at the University of Illinois at Chicago, and Thomas A. DeFanti, a professor at the University of Illinois at Chicago, are also credited with creating the CAVE. The CAVE can come in quite a few forms, but the most complete CAVE is a six-sided fabric lined room using one projector and one mirror to light each side of the room, from the outside, with features from a simulated virtual environment. One example of a four-sided CAVE can be found in Figure 2. While this figure doesn’t depict a complete six-sided

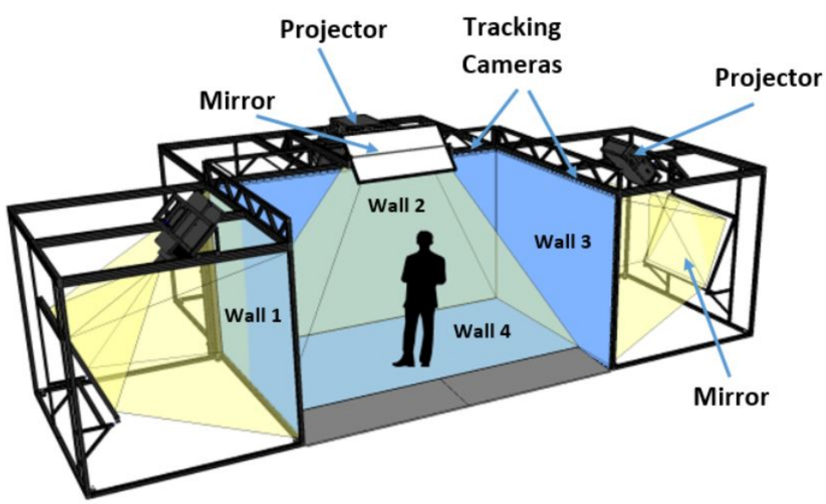

Figure 2: Annotated diagram of a four-sided CAVE system with mirrors from NASA’s GRUVE Lab [15]

CAVE, the same principles apply for any number of sides on a CAVE. This figure also shows the tracking cameras which allow the user inside of the CAVE to move around and interface with the virtual environment in various ways. Originally this technology used electromagnetic sensors to track movements, but has since moved to infrared cameras to eliminate interference common to electromagnetic sensors. This technology has been widely adopted and you can find CAVE systems, despite their high price and long setup times, at many universities and research facilities. This technology has also evolved, as of 2012, to produce the CAVE2 [6], which is based on LCD panels rather than full projection. The CAVE2 was produced by the Electronic Visualization Laboratory (EVL) at the University of Illinois, Chicago. The two most significant aspects of the CAVE2 system are that it's cost is considerably lower than the CAVE system, and it allows for a more spherical shape to the environment, which allows for much greater realism. The CAVE2 also boasts ten times the 3D resolution of the original CAVE.

Many other inventions happened after the CAVE to produce 3D graphics, but no real progress in VR devices happened until 2010, aside from large scale VR hardware in the use of theaters and amusement rides. In 2010, the prototype for the Oculus Rift was released. This headset boasted a 90-degree field of view, which wasn't previously seen before in HMD based VR. The Oculus Rift would then be shown off at E3 and Facebook, now Meta, ended up buying it for three billion USD. Meta and Oculus later got sued by Zenimax, over the Oculus on grounds of dissemination of company secrets, who won after Meta settled out of court. The next important step in HMD innovation was done by Valve who discovered, and freely shared, low-persistence displays which make smear-free HMDs for VR possible. This technology would then be adopted by all HMD manufacturers going forward. In 2014 Sony announces Playstation VR (code name Project Morpheus). In 2015 the HTC Vive would be announced and it would use tracking technology which utilized "Lighthouses" or "base stations" that use infrared light for position tracking of the VR headset and controllers. In 2015, Google announced Google Cardboard which would bring VR to a brand new audience by utilizing smartphones for VR. Going forward, almost every large tech company either had a VR HMD released or a VR/AR group at the company.

In the current era, each of these HMDs are starting to carve their own niches in the VR space. Despite these niches, most HMDs can be categorized based off of their tracking method and connection type. Tracking methods are either outside-in or inside-out. Outside-in tracking is where the HMD, and other peripherals, are being tracked by outside sensors. Some HMDs that offer this tracking are the Oculus Rift, Valve Index, HTC Vive Pro, HTC Vive Pro Eye, HTC Vive Pro 2, and the PS VR system. Inside-out tracking is where the HMD is tracked via integrated sensors that detect changes in the position of objects in the environment. This type of tracking can be done either with or without markers placed in the room. Some HMDs that offer this tracking are the HTC Vive Cosmos, Microsoft HoloLens, and Meta Quest 2. The HTC Vive Cosmos Elite is a particularly interesting VR headset due to the fact that it allows for both inside-out and outside-in tracking due it's replaceable face plates. Connection types for HMDs mean that the HMD is either connected to the PC to be able to work, or it has a standalone system that allows the headset to work without a PC attached. Most headsets are not standalone, some that are standalone are the: Meta Quest, Pico Neo 3 Link, HTC Vive Focus 3, and HTC Vive Flow. Currently, the product line with the most flexibility and diversity is done by HTC Vive, especially now that Oculus/Meta no longer produce any HMD besides the Meta Quest 2.

3 Current Research

Most current research is in the software and tools for VR since creating unique and usable headsets is expensive and is already being done by large manufacturers. There is quite a bit of research dedicated to reducing or better understanding virtual reality sickness (VR sickness). There are also quite sizable projects designing applications to train or educate individuals/-groups.

3.1 VR Sickness and Health Risks

VR sickness, which is also called cybersickness, closely resembles motion sickness in terms of symptoms. This sickness comes with a few known symptoms: Nausea, balance disorder, and vomiting. VR sickness is generally understood to be caused by a disconnect between what our senses are telling us and what is actually happening. This is called sensory conflict theory and it has been used to understand motion sickness for many years, though there are many theories relating to this topic. An example of what sensory conflict theory is presenting: If a person is in a car and looks out a window, they may get motion sickness due to the fact that their eyes see a fast moving landscape, but they personally are not moving. This would explain why some people's motion sickness gets better when they look at objects in the environment that are further away, and are thus not moving as fast due to parallax. There is also a notable conflict in the literature between deciding if gender has a role to play in VR sickness with more recent research dictating that there is no significant difference [21, 27], while later research explains that women are more susceptible to VR sickness [10, 18]. It is not clear why this conflict in the literature exists, but due to the almost ten years of time difference between the studies it could be quite a number of things.

Though not currently being researched very heavily, it has been shown that VR can be problematic for a user's sense of presence and can even induce dissociation [1]. This work shows the symptoms of depersonalization and derealization had a significant increase (4.9% - 14.5%) in their thirty participants when exposed to a virtual environment in VR. These symptoms exist to some extent in every individual, but in both the cases of participants with high and low amounts of these symptoms/feelings already, there was a significant increase in these symptoms/feelings. Due to these findings: the more realistic a virtual environment, the more careful developers need to be in showing a user unsettling and graphic things as they could severely impact their users world view and sense of self outside of the real, objective, reality. Quite a bit more research should be put into this topic, in particular, if the dissociation issue should be listed as a part of VR sickness, meaning that they effect the same people in the same way. It would also be interesting to see if a number of factors change the amount of disassociation in the participants: the amount of realism, resolution of the environment, interactions available, multiplayer, ambient sound or background music, HMD differences, and/or locomotion techniques. It also isn't clear how long these symptoms last.

Lastly, there is another important health risk that users and developers of VR must be aware of. HMDs can be quite heavy at around 600g or 1.3lbs, so using them for extended duration and at a fast movement rate can be slightly dangerous. If the user's back, neck, or spine are sore do not continue to use the HMD. This disclaimer is brought about due to a very recent report of a German VR gamer breaking their C7 neck vertebra while playing VR [3]. This is the first ever case of a VR induced stress fracture, despite the sixty years of HMDs before this point. More cases are likely to pop up due to VR's growing proliferation, however.

3.2 Locomotion

Due to the fact that VR is a fairly new technology, a lot of work is being put into making it more usable and user friendly. One issue for VR is in typing, which is covered extensively in [13]. Another issue is in locomotion. Physical locomotion, which is the process of physically moving and having the VR system track and display this, by default this isn't really that practical. Outside-in tracking causes this type of locomotion to be very limited due to the need to stay in range of a sensor. Inside-out tracking makes this locomotion a bit more plausible, but still relatively useless by itself as you're still tethered to a PC. The major downside to this locomotion technique not being usable is in the fact that physical bipedal walking comes the most naturally to humans and thus it makes VR sickness less likely. This is why redirected walking [19] was developed in 2001. Redirected walking rotates the environment around the user slowly and, almost, imperceptibly. The principle relies on the fact that humans will naturally auto-correct their movement in order to navigate through an environment. As they naturally auto-correct their physical rotation in order to direct themselves to an objective in their virtual environment, they create a curved physical path, thus increasing their available play space without even realizing it, as they only think they've walked in a straight path in the virtual environment. Many other publications have claimed they've improved on this concept using specific algorithms and machine learning [2, 12, 25], but the core concept remains the same.

Another physical locomotion technique is walking in place. This technique allows walking by having the user bring their legs up in a walking-like motion, but not actually move to anywhere physically. This technique is seldom used in favor of some of the other techniques listed below. There is an iteration of this technique that is used regularly, which is held-in-place walking or gait-negation. This technique utilizes a third party peripheral to hold the user in place as they walk or run. Two of these peripherals are the "Virtuix Omni-directional VR Treadmill" and the "Virtuix Omni One VR Treadmill". Both utilize a very slippery surface, to reduce friction of feet moving, and trackers attached to the user's shoes to detect movement. The way these two treadmills differ is in their holding mechanisms. The Omni-directional VR treadmill, uses a ring around the user that the user can lean against to move towards a virtual location. The ring itself is set to a specific height for each user before they get into the VR environment. As the user leans they slip and can walk or run forward towards that virtual location. The "Omni One" [26], as seen in Figure 3, holds the user by strapping them into a full vest that is suspended at a given height. This particular model reportedly allows the user to jump and crouch as well, something that the previous model did not. This treadmill is not currently out on the market yet, but they do have demos that make this treadmill seem very interesting for research going forward.

There are quite a few other locomotion techniques. Joystick walking is where the user utilizes a joystick or a trackpad of some sort to move their avatar in a given direction. This approach can have six degrees of freedom due to the nature of the controllers. This approach also has a significant risk of VR sickness due to the fact that the user's perspective is moving, but the user themselves are not physically moving. This technique doesn't require the use of trackpads or joysticks, but some continuous actuator is required as well as some sort of vector. For example, the trigger on a controller could be the actuator and the rotation of the controller could give the angle of the vector, while the magnitude is fixed programmatically.

Teleportation based movement can come in quite a few forms. The three most prevalent forms are what we'll call: direct teleportation, preset teleportation, and avatar movement-based teleportation. Direct teleportation, in this case, refers to teleporting directly to the location that the user's cursor is. The cursor will generally be shot out from the tip of the user's controller and fall rapidly until it collides with the floor. This then creates a target on the ground that the

Figure 3: The new Virtuix Omni One VR treadmill [26]

user can then teleport to by pressing a button. This is by far the most common teleportation method and it is the default inside of the "SteamVR Home" [7] application (the default VR launcher on a PC). "SteamVR Home" also uses preset teleportation. This teleportation allows the user to teleport only to specific location in the environment. These locations are either single points that allow the cursor to snap directly to them, or they are larger areas that utilize a small amount of direct teleportation. The combination of direct and preset teleportation results in areas that the user can teleport inside of, but are still defined by the developers. "SteamVR Home" utilizes all of these teleportation methods by having a preset area that the user can teleport inside of and specific points in that area that the user can teleport to in order to select and change specific aspects of the virtual environment. The last teleportation method, avatar movement-based teleportation, is quite interesting. This teleportation method is the least common, but it is a very novel approach. This approach aims to solve a social VR problem, where teleportation generally feels very off putting to the people around the user teleporting. This method animates the user's avatar and makes it walk to the location the user's cursor is focused, while keeping the user's camera fixed in their current position. When the avatar makes it to their desired location, the user can then teleport their camera to that location. This means that the user temporarily sees in third person and can watch their avatar walk to a location. This locomotion technique can be seen in the application, "VR Chat" [8], which is a social VR platform. It is important to note that none of the teleportation methods can move with the six degrees of freedom that the joystick allows, but they also have significantly less risk of VR sickness associated with them.

3.3 Education and Training

Education in VR has always been a key field where VR shines. In recent years, training in diversity, equity, and inclusion (DEI) have been large topics of discussion. Virtual reality has been used to further this type of training to make users more engaged and present rather than simply for compliance. Technology in this specific area has been focusing on social VR, 360° video, and speech recognition, to name a few. One DEI VR application [20] attempted this type of training and met with resounding success from participants. The users in this study responded to the training's questionnaire and the researches released the following data points: 90.8% felt moderately to completely engaged; 60.5% reported feeling somewhat present of very present during the VR experience; 94.7% of respondents agreed or strongly agreed that VR was an effective tool for enhancing empathy; 85.5% agreed that the VR experience enhanced their own empathy toward racial minorities; 18.4% reported discomfort in VR; and 67.1% stated that they believed the VR experience would change their approach to communication. These survey results are overwhelmingly positive, and they validate what corporations have started to do already, which is to train their employees in DEI using VR.

Training in VR not only has the benefit of generally being more immersive and causing trainees to feel more present in their training, it also has the benefit of allowing accurate and realistic simulations and training for dangerous situations virtually. From fire simulations based in a user's home town to training for mining and construction related difficulties, virtual reality training can help save many lives and prepare individuals more accurately than many other techniques. This is also true for training in VR for medicine. One paper, depicting the results of a randomized, double-blinded study on VR training for the operating room in gallbladder surgery [23], found that VR training was 29% faster than a traditional approach and that non-VR-trained residents were nine times more likely to transiently fail to make progress. Non-VR-trained residents were also five times more likely to injure the gallbladder or burn non-target tissue. Mean errors were also six times less likely to occur for the VR-trained group.

Indeed, the effectiveness of VR training and education can be very worthwhile for quite a few fields. However, this doesn't mean that VR is correct for every situation and field. To give more understanding as to when to use VR for training, a paper titled, "Reasons to Use Virtual Reality in Education and Training Courses and a Model to Determine When to Use Virtual Reality" [17] shows insight into this problem. This paper advocates for the use or consideration of VR when: Simulations could be used; teaching or training using the real thing is dangerous, impossible, inconvenient, or difficult; a model of an environment will teach or train as well as the real thing; interacting with a model is at least as motivating as with the real thing; Travel, cost, and/or logistics of gathering the class are too high compared to using VR; shared experiences and environments are important; the creation of the environment or model is part of the learning objective; information visualization is needed; a situation needs to be made to feel real; improving perception on specific objects; developing participatory environments and activities that can't exist in the real world; teaching tasks that involve dexterity or movement; a want to make learning more interesting and fun; accessibility for disabled people; or where mistakes in the real world would be devastating or demoralizing. This paper also describes the reasons not to use virtual reality for training/education: no substitution is possible; interactions with real objects is necessary; using a VE could be physically or emotionally damaging; using a VE can result in the confusion between reality and the VE; or VR is too expensive given the learning outcome.

4 Areas for Improvement

VR has a number of areas that still need research. One issue that will be a problem for future VR applications is user verification. Currently, most verification is done via generic username and password in a PC environment. This is secure up until the user puts on the HMD. Once the user puts on the HMD, it could be anybody underneath the headset. This has caused a number of research papers to come out on how to verify users in VR via movement and how to track and visualize movement in VR [11, 14, 16]. There has also been interesting work on signature validation using data gloves [22]. Despite these verification techniques, more research needs to be put into the continuous verification of users due to the fact that users can take their headset and swap with another user at any point in an application. This will be particularly relevant and important when VR is more widely adapted in training, education, and the workplace.

Data gloves are integral for the future of VR due to their versatility and natural movement. The hardware itself does need a bit of work, in most cases on it's tracking capabilities. This is particularly true for the actuation and range of movement of the hand and fingers. Largely, the hardware is usable. The main issue with data gloves is on the software side of things. Gesture recognition is possible with these gloves [4], but out of the box they recognize few, if any, gestures. Developers who use these gloves also, generally, have to develop for each glove manufacturer's SDK. More research and development must be put into generalizing these SDKs so that developers can program for data gloves as a whole, rather than individual types of gloves.

Implementing these abstraction layers between VR technology and VR applications is incredibly important, not just for data gloves, but also HMDs. The industry is moving towards this abstraction layer called, "OpenXR" which is an application interface that most HMDs use. Oculus is currently the only popular HMD that isn't fully integrated with OpenXR yet, but the company has decided that after August 31st, 2022, all developers will need to switch to developing with OpenXR and old SDKs will be unsupported. Both Unity and Unreal Engine 5 have support for OpenXR and each have a VR template supporting the features in OpenXR.

VR templates are a good step forward in VR development; however, most have very little features actually associated with them. This needs to change in order for VR to be easier to develop for. These templates do not have support for many interactions and peripherals associated with VR development, and can often not have many locomotion features, selection features, 3D models specific to VR, and multiplayer. These are all features that need to be specifically tailored for VR and would help developers immensely in creating applications quickly.

Typing in VR needs more research and development. Typing has always been a much slower process in VR than in traditional interfaces. This work aims to help this issue, but it is not a complete solution by far. Natural typing is immensely important due to the fact that most applications require it. It's part of a large population's day-to-day activities and VR should be able to accommodate something like it easily in order for it to grow into a useful day to day platform in work, education, training, and entertainment.

As with any 3D environment, VR needs to have better and more realistic graphics. Photogrammetry is a technique often utilized to help this issue because it can create convincing 3D models via the use of various cameras and sensors. These sensors either take a scan of a physical object and then convert those scans into models, or the sensors require the user to take multiple pictures around the object and then the software will stitch together the model. Regardless of the method used for photogrammetry, the result is often both a 3D model and a texture to go on the model. Photogrammetry can go a long way in making 3D environments look realistic, but it's a long way away from perfect. Even in a room created with photogrammetry, shadows and textures can create an unnatural and "uncanny valley" feeling. The world around the user can look almost real, but there are slight differences that make it look like CGI and not an actual environment. Most people could not put it into words why the scene looks strange, but they often notice that it isn't correct.

Overall, VR has quite a few issues to iron out before it can widely be used, but the potential of it is truly remarkable. There may be a world in the future where education is done via group experiences in VR to participate in science experiments and minutely control the intricacies of the simulation and playback speeds. Where training is done in VR to prepare workers for any situation. Where desk jobs and programming are done in your own home, yet you're virtually at the office and can still interact socially with your coworkers. Where joggers are virtually running with their friends all over the world, yet jogging physically alone in their own neighborhood. Truly, VR/AR/MR/XR have an incredible amount of potential in connecting us socially, educating the masses in new, unique, and effective ways, entertaining in a unique and interesting medium, and creating safe and efficient work places.

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