Virtual Reality Primer
With an Emphasis on Camera-Captured VR

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Warner Bros "Into the Storm" VR Experience

What is Virtual Reality (VR)?

Virtual Reality, which can also be termed immersive multimedia, is the art of simulating a physical presence for the audience in places both real and imaginary. It usually involves two senses; sight and sound. But a growing body of experimentation and innovation is working to bring touch, smell, taste, as well as balance into the experience. This article is an attempt to give an overview of the current state of entertainment-related Virtual Reality, with an emphasis on live VR experiences. The technology, art, and business of VR are evolving rapidly. Start-ups, new deals, projects, and tech breakthroughs are being announced daily as people leap at this new art form and seek a share of a market that is estimated to reach $30B by 2020[1].

The key property that distinguished VR from all previous media types is "presence." Movies, videos, and other linear art forms have perfected the language of guided storytelling within the rectangle of the display frame. Videogames allow for interactivity with a story gameplay setting, as well as "agency;" the ability to interact with the environment and have the environment respond to your actions.

Presence is the psychological sense of 'being there,' of actually being immersed in and surrounded by the environment. It works, at least in part, because there is no distance between you and the environment. There is no frame limiting your view into the environment. Objects and characters can invade your personal space. Spatial audio software can place sounds all around you that maintain their expected position as you turn your head.

Even with only the ability to look around as a passive observer of the world around you, being surrounded by images and sounds creates a clear sense of presence that differentiates VR from other art forms.

[1] Augmented/Virtual Reality to hit $150 billion disrupting mobile by 2020, Digi-Capital, April 2015, http://www.digi-capital.com/news/2015/04/augmentedvirtual-reality-to-hit-150-billion-

How does Virtual Reality differ from Augmented Reality?

The most simplistic way to understand the difference between virtual reality (VR) and augmented reality (AR) is to think about the relationship between where your body is located and what you are seeing and experiencing; what is actually around you versus what is artificial.

If you are holding a phone or tablet in front of you, with the camera on, as you physically walk down an aisle in a grocery store, and the screen shows you information about the products on the shelves – price, ingredients, videos of corporate mascots, etc. – that is augmented reality. The world that you would normally see if you walked down the aisle without the screen is being augmented – enhanced, supplemented, added to - with additional data and experiences. If you sat at home and directed a robotic camera to roll down the exact same aisle in the real grocery story, so you saw the exact same information on a screen mounted on your head from the comfort of your chair, that is virtual reality. You are virtually – nearly, almost – but not really there in the grocery store aisle.

Full AR and VR are endpoints on a spectrum of experiences. If, as with Google Glass, you primarily see the real world around you, but there is a little window of additional information in your upper right field of view, then you are having a basic AR experience. If you are seeing both the real world and projected objects in your field of view (ex. heads-up displays, Microsoft Hololens, Magic Leap), then you are having an AR experience. As the percentage of the image within your field of view shifts from what is actually there to what is artificially mapped on it, you are transitioning from what would be called an augmented reality experience to a virtual reality experience. If the glasses went dark and you could only see projected objects, regardless of whether they are live or computer generated, then you are having a full VR experience.

Today AR and VR are discussed as separate experiences for marketing and branding purposes. As innovation continues and products begin to bundle the technologies into a single product, the conversation will shift. We may even get a new term for it. (Who would have predicted that the term 'movie' would dominate and last a century?)

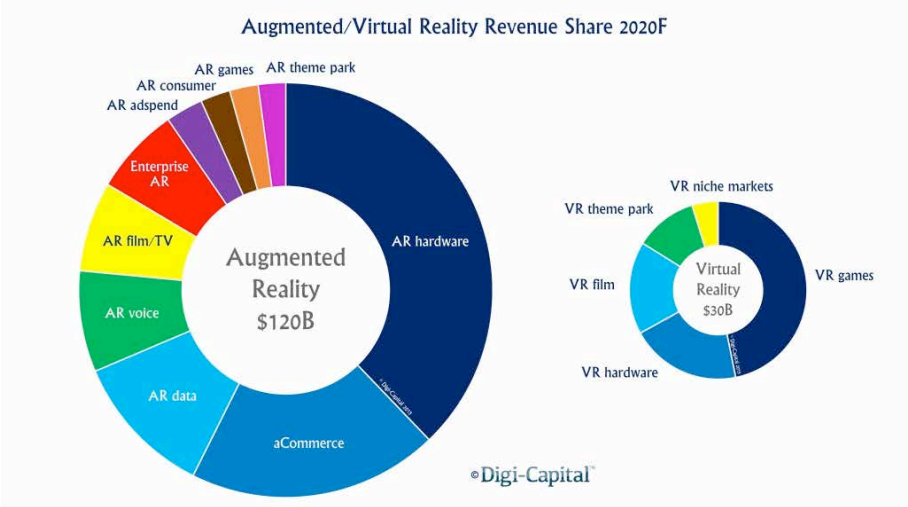
Market size – forecasts

Prior waves of VR required specialized equipment for deep-pocket customers and targeted niche applications; oil and gas, the military, medical research. Just as advances in technologies in related mass markets made digital cinema possible in the early 2000s, the current wave of VR has been enabled by the mass adoption of mobile platforms with high resolution display screens, the widespread deployment of wireless technologies, and advances in computing power, compression algorithms, camera technology, position tracking, and other complimentary technologies.

All market projections should be read in the context of a much-discussed, new consumer proposition (e.g. VR) with as-yet unidentified 'killer apps.'

Market research firm KZero[2] projects that by 2018 there will be 170 million VR gamers, of whom 29 million are projected to be willing to pay an average of $14/month for access to VR games. They project $8.6B in annual VR Gaming revenue in 2018, equally divided between spending on hardware and software.

Digi-Capital[3] evaluated all markets and products, including B2B hardware and software, and projects a $30B VR market (~20% going to VR films, ~45% going to VR games) and a $120B AR market in 2020.



[2] Virtual Reality Software Revenue Forecasts 2014 – 2018, KZero Worldwide, http://www.kzero.co.uk/blog/virtual-reality-software-revenue-forecasts-2014-2018

[3] Augmented/Virtual Reality to hit $150 billion disrupting mobile by 2020, Digi-Capital, April 2015, http://www.digi-capital.com/news/2015/04/augmentedvirtual-reality-to-hit-150-billion-disrupting-mobile-by-2020/#.VYQ2-mBiBrh

PiperJaffray projects "the market size for VR, excluding hardware, from live sporting events, concerts, education, adult content, social experiences, movies and gaming reaching $5.4B by 2025. While a market size of $5.4B may seem small, this number is content only and excludes hardware, which we estimate to be $62B (500M headsets at a $125 ASP) in 2025."[4]

CCS Insight projects[5] 2.2M VR Head Mounted Displays (HMDs) will be sold in 2015, rising to 20M HMDs in 2018. They also expect that 90% of the 2.5B smartphones sold in 2018 will be VR hardware compatible.[6]

Minimum viable versus more fully realized VR experiences

When designing a VR experience, it is important to think about the type of end-user experience that you want to create, and work back from there. As with other art forms, the audience will come for the experience, not the technology. But the technology must be matched to the experience so it can disappear into the experience rather than draw attention to itself.

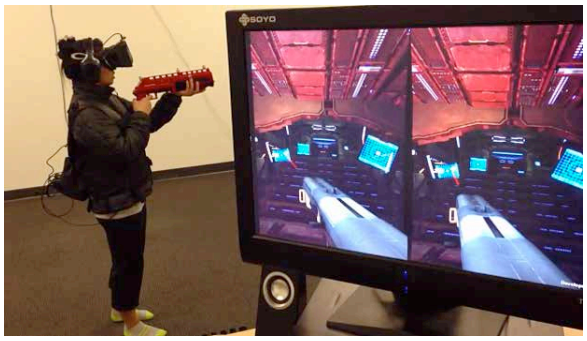
With that in mind, there are currently two categories of VR experiences, each with their own communities building hardware and applications for them; minimum viable VR experience and more-fully realized VR experience.

The minimum viable VR experience is expected to be the mass market experience. It relies on cell phones, tablets, and other mobile devices for the display, audio, and in some cases controls, head-tracking, and other experience elements. Examples are Samsung Gear VR, Wearality, Google Cardboard and similar 'phone-case' products. They currently lack the ability to track leaning in for a closer look at objects. But they can track the user's head turns, fill her field of view (FOV) to varying degrees, and provide audio cues through headphones. Almost every cellphone currently on the market is VR-compatible. The cost of a minimum viable VR experience to the consumer is so low (branded copycat Cardboards are promotional give-aways; content is currently free) that most consumers will be willing to try VR multiple times even if a few of the experiences are bad.

Gear VR with Galaxy Note 4 phone / Oculus Rift with Oculus Touch controllers

[4] Next Mega Tech Theme is Virtual Reality, PiperJaffray, May 2015,
[5] CCS Insight press release, June 18, 2015, http://www.ccsinsight.com/press/company-news/2251-augmented-and-virtual-reality-devices-to-become-a-4-billion-plus-business-in-three-years
[6] Virtual and augmented reality devices to be $4bn market in 2018, Wired.co.uk. June 18, 2015, http://www.wired.co.uk/news/archive/2015-06/18/virtual-reality-sales-2018

The more fully realized VR experience involves a dedicated Head Mounted Display (HMD). This sophisticated, higher-cost VR experience includes lean-in tracking, and can include hand tracking, body tracking, eye tracking, brainwave monitoring, haptic feedback, specialized controllers, and other capabilities and devices. Currently these HMDs must be tethered to a computer due to computational power and bandwidth requirements. Examples of HMDs are the HTC/Valve Vive, Oculus Rift, Sony Morpheus, Fove, Razer, and StarVR. Examples of peripherals are Leap Motion hand-tracking, and Sixense hand- and feet-tracking, Control VR body suit, Tactical Haptic's Reactive Grip, Birdly's flying platform, and Virtuix Omni treadmill controller.



VRcade Combines Motion Capture with VR Headsets

4D theatrical and arcade experiences, which can include moving seats and physical effects, are examples of destination VR experiences. Examples are the CJ 4DX theatrical installations[7], The Void arcade in Salt Lake City[8], VRCade's full body gaming systems for Dave & Buster's[9], and the proposed Landmark Interactive Virtual Experience in China[10].

VR can also be divided into passive versus active experiences. In a passive VR situation, the end-user is being taken on the storyteller's journey through the world. The end-user can look around during the journey, but they have very little control over what happens. At the other end of the spectrum is the active VR experience in which the end-user can make choices that change what she experiences and how the world responds to her. This includes gameplay and story-path choices.

Another parameter that spans a spectrum is live action versus rendered VR. In a purely live-action VR experience the end-user is locked into the camera positions. She can look around, but cannot wander into the world. A fully rendered VR experience can allow the end-user to range freely through the space. As with VFX in

[7] http://www.cj4dx.com

[8] 'The Void' is a VR Experience which Fuses Physical and Virtual Reality Environments, Road to VR, May 5, 2015, http://www.roadtovr.com/the-void-is-a-vr-experience-which-fuses-physical-and-virtual-reality-environments/

[9] VRcade Releases World's First Wireless Virtual Reality System at Dave & Buster's, 7/15/15, http://globenewswire.com/news-release/2015/07/15/752421/10141861/en/VRcade-Releases-World-s-First-Wireless-Virtual-Reality-System-at-Dave-Buster-s.html

[10] New VR Theme Parks from Landmark Entertainment Group to "Fuse Art, Culture, and Retail with Virtual Reality", June 8,2015, http://www.landmarkusa.com

cinema, these are endpoints on a spectrum, since rendered objects can be inserted into the live action content and visa versa. This spectrum is distinct from active versus passive VR in that a fully rendered VR experience can be designed to be purely passive and observational.

The magnified importance of Audio and User Interface (UI)

You only look forward with your eyes, but you hear all around you through your ears. You have positional 360 surround plus over and under hearing. In VR, as in gaming, the world can exist all around you. Spatial audio and audio cues can be more important than the visual experience in a VR experience. They can even be the make-or-break element in some VR experiences such as social VR. In social VR, or virtual worlds, you are an avatar in a 'room' with other people's avatars. The room works best when you can locate individual voices in the cacophony from spatial audio cues. Janus VR and Altspace VR are examples of social VR.

The end-user has control over their actions and receives information and feedback from within the VR environment through the UI. The UI design can involve peripheral devices and external detectors as well as on-screen and audio elements. In user interface design for gaming and DVD there is a rectangular frame in which to place information and interaction options. How do you design and position that information and those interaction options when there is no frame and you cannot predict where the end-user is looking? How do you integrate the UI design into the experience so that it is part of the experience and not a 'mechanic' overlay on the experience that distracts the end-user. These are key questions fundamental to the language of VR that are being actively studied and tested.

Deep dive into live action VR

The remainder of this paper is going to focus on live action VR, covering the current state of the technology, as well as some considerations for the art of live action VR production. Particular emphasis will be given to streaming live action VR, because streaming is the driver for rapid innovation in live capture VR. Put simply, there is a widely held belief in the VR community that there is an immediate market, and the potential for premium pricing, for the minimum viable VR experience in streaming concerts, sports, and other mass-audience events in VR if it can be done 'right.' Tools and techniques developed for streaming will directly port over to post-produced live action VR productions, enabling lower cost productions for smaller-market VR experiences.

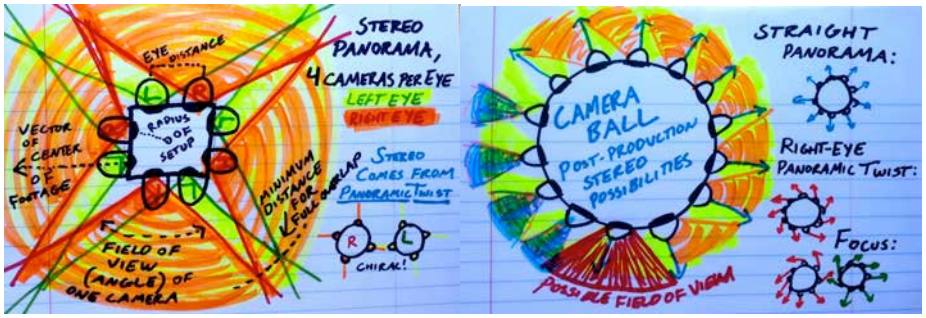
Cameras, rigs, stitching, and video capture types

There are a wide variety of 360 surround, half-sphere, and full-sphere camera rigs to choose from. They range from the Ricoh Theta and Giroptic at the low end (under $500), to the 14 RED Dragon 3D HypeVR rig at the high end. Some of these cameras are single-body integrated VR rigs, with the cameras in fixed position. Ricoh Theta, Giroptic, and Immersive Media's Hex camera family fall into this category. Others take existing cameras and place them into multi-camera configuration rigs. At the consumer end, 360 Hero, Freedom 360, and Google sell rigs that hold multiple GoPro cameras. The GoPro camera count and rig configuration depends on artistic

considerations, whether it will be 2D or 3D (via either paired camera 3D or computationally created 3D), and of course budget. At the high end, NextVR and HypeVR use multiple REDs in custom mounts. A number of VR content creators we spoke to recommend renting, rather than buying, rigs, because the rigs are evolving rapidly and the money is better spent in postproduction. VR rig rental house Radiant Images was mentioned often.

GoPros in 360Hero rig / Immersive Media's Hex camera / NextVR 6-Red 3D VR rig

For all of these multicamera solutions, the images must be stitched to create the seamless VR experience. Many of the integrated camera solutions also come with stitching software for a user-friendly consumer experience. Increasingly this is also happening with the custom rig solutions, many of whom have their own 'secret sauce' stitching approaches. The two leading VR stitching software vendors are Videostitch and Kolor. Videostitch does real-time stitching and markets itself as 'the' solution for streaming VR. Kolor was recently purchased by GoPro, so expect their multicamera VR rig solutions to soon have a very user-friendly stitching workflow. The recently announced GoPro / Google partnership on the Jump 360 16-camera platform includes uploading the video to the Google cloud where the video streams are automatically stitched into a 360 computationally generated 3D experience that can be posted to YouTube.



Images are stitched together where they overlap to form a continuous image

Note that image distortion can increase toward the edge of a captured image. The fewer cameras used to capture live VR, the more this distortion can impact the stitching and result in visible seams.

The problem is amplified when shooting paired-camera 3D VR. Not only must the stitch be seamless, but the corrections must take into account proper left-eye / right-eye alignment (including consideration of the nodal point). The GoPro/Google

Jump and the Jaunt cameras avoid this problem by computing the 3D image from the overlapping 2D images in their 16-plus camera rigs.

In addition to the products mentioned above, there is a whole community of creatives and technologists building their own rigs for better performance, to meet their unique needs, or to make their product or service stand out.

Live VR capture R&D

Live capture videography using traditional cameras can create high resolution all-enveloping experiences, but the image files do not contain the data needed to allow the end-user to wander within the scene. Current technology only allows the end-user to look around from the perspective of the camera's position. New image capture and processing technologies are being developed to overcome that limitation.

At the recent FMX 2015 conference, OTOY and Paul Debevec demonstrated[11] the first ever light field captured still image of a full sphere of a real world environment. The end-user can move around the space within the sphere and look around objects in a limited way (e.g. experience parallax).

Another approach to allowing the end-user to move within a live real-world space is to capture the space from a variety of angles and build a model of the 3D space by interpolating among the images. Some people believe that all of the technical pieces to enable this approach currently exist, especially for rendering it in post production. It will take major increases in computing power, improved stitching and modeling algorithms, and solutions to other tech, artistic, and business issues to make live real-time modeling of live scenes a reality.

[11] OTOY demonstrates first ever light field capture of a real world environment, producing photorealistic, navigable virtual reality experience, May 7, 2015, http://home.otoy.com/otoy-demonstrates-first-ever-light-field-capture-for-vr/

Audio capture

TetraMic from Core Sound / Eigenmike from MH Acoustics

Audio can be more than half of the live VR experience because it lets the end-user hear what is going on all around them while they are looking in one direction. The type of sound design you want to provide the end-user (and archive for future reuse) will shape how you capture live audio. Point source mikes (ex. lavaliere) are good for capturing fundamental audio clearly. Directional and Omni-directional are good for ambient sound. Omni-binaural (simulates human ear capture; ex. 3Dio) or ambisonic (full sphere surround capture; ex. Tetramic, Eigenmike) mikes are good for capturing the direction of every sound. All of this can be reshaped in real time at the mixing board for output to the distribution stream.

The status of workflow, distribution, and standards

VR production workflows are extremely immature. The language of VR and the needs of the workflow are still being defined. Live streaming VR productions currently have two choices, either kluge together a workflow and debug it in-house, or contract with an end-to-end solution provider (ex. Immersive Media, Vantage.TV, NextVR) and offload the problem to them. The latter is the easiest approach, but the former gives your staff the opportunity to provide feedback to vendors and in-turn shape overall workflow development.

Websites currently aggregating VR content for consumer download include Vrideo, WEVR, Jaunt, Google Play, NextVR, YouTube 360, Littlstar, Vantage.tv, Oculus VR, and Samsung's Milk.

Note that YouTube 360 and some of the others offer player apps for mobile devices that allow playback via "touch, gyroscope or VR."[12] Viewing the video on a mobile device without a 'phone-case' VR viewer, the end-user can swipe the screen (e.g. "touch"), or move the mobile device around in space (e.g. "gyroscope") to move around in the 360 image. This is not considered a true VR experience, but it does make the VR content available to a huge additional market.

Live VR cameras abide by the MPEG-4, H.264, H.265 standards. File size, frame rate, resolution, compression, metadata, and other issues currently under discussion within SMPTE, are topics of ongoing experimentation within the VR production community.

The Audio Engineering Society has published AES69-2015 standard to address the evolving field of 3D audio. It defines a file format to exchange acoustic data in multiple forms, including head-related transfer functions (HRTF) and directional room impulse responses (DRIR).

OSVR, the Open Source Virtual Reality group, is working on standards for the distribution and end-user equipment and experience (see http://www.osvr.com/join.html for a map of their committees). Over 70 companies and universities are OSVR members.

The IEEE has held conferences on the topic of VR and standardization (http://ieeevr.org), but has not initiated work on any specific topic.[13]

Language of live VR storytelling

Live TV production teams have decades of experience finding and showing the viewer the best shot at every given moment in sports, red carpet, concert, or other live event. Live VR will not replace that viewing experience. Few viewers will see live VR as an opportunity to avoid seeing the best camera angles, instant replays, highlights, and other elements of a professionally directed and framed program. Live VR will find a new, as yet undefined role. Perhaps it will be a fixed camera position that seats the end-user next to some interesting people with a 360 view of the event (ex. a seated position on the 50 yard line at an NFL game, or a front row center seat at a concert), while the traditionally directed live feed is a virtual screen locked into their upper right field of view. Much experimentation and market research will go into determining what works. Here are some current thoughts on the language of live VR, aggregated from workshops and interviews with current practitioners conducted by the USC Entertainment Technology Center.

Have a reason to shoot in VR. Be able to articulate what value is added by being able to look around. If you can accomplish your artistic goal through other, more traditional media, save yourself a lot of work and don't bother with VR.

The key property of VR is "presence," the sense that you are actually there. Therefore think of the camera as the audience's head. First decide whether you want

[12] Bubl Mobile and Virtual Reality, http://www.bublcam.com
[13] IEEE Standards Association is discussing Augmented Reality, http://standards.ieee.org/innovate/ar/index.html

to shoot from a 1st person or a 3rd person perspective. If you are shooting 1st person, decide if the end-user will be standing or sitting while events are happening around him. Once you establish that, be consistent unless changing the perspective is part of your experience design. If you are shooting from the 3rd person perspective, camera height matters less because the end-user knows they are outside the action and will accept variations.

High resolution live VR capture requires stitching images from multiple cameras together. Until stitching technology is perfected, avoid knowingly placing objects of interest in the seam between images.

Audio is a fundamental element of the VR experience. It cannot be emphasized enough. Learn to capture it properly and use it creatively.

The technology used to shoot live VR should either be a natural part of the experience or be hidden. You expect to see lights and cameras at a sports event, concert, or live news broadcast. You don't want to see the crew if you are shooting reality TV.

"The Mission VR", a film by New Deal Studios and Jaunt VR (Jaunt camera, TetraMic)

Because the end-user can choose where to look and what to do within the VR environment, the content creator must use subtle coercion to guide them. Techniques include providing less detail or lower resolution in areas that aren't important. For example, only put readable text on objects that you want the end-user to read. Provide better lighting and/or audio cues down pathways that you want the end-user to look at. An example of creative misdirection is putting a yapping puppy in the scene for the end-user to watch while the zombie army sneaks up behind him.

Lens choices can impact both end-user experience and production costs. One production company shoots live VR sports events using a rectilinear lens facing the action, and fish-eye lenses filling in the surround. The end-user gets the detail of the action and the ambient sense of the surround. (Aside; xRez Studios, a production company that specializes in post-produced large format immersive nature programming, sometimes captures canyon fly-throughs by shoot very high resolution video forward and stitching it in post to panned very high resolution still images for the surround portion.)

Camera movement, based on audience reaction to date, should be limited to stationary position and constant velocity shoots. Acceleration and deceleration can trigger simulation sickness in the end-user. The one possible exception to this

guideline is placing the camera inside a moving vehicle, where the end user is stationary relative to his surroundings even as the world outside the window races by. Recent research[14] has found that placing a nose, glasses, or other fixed object in the end-user's field of view creates a familiar reference point and may prevent motion sickness in VR. Also, avoid camera movement that isn't directly tied to the end-user's head movement.

Jump cuts and dissolves do work in VR and can be used effectively to advance the consumer through the narrative.

As stated earlier, the user interface (UI) is how the end-user controls their actions and receives information and feedback from within the VR environment. In live VR, the UI can, for example, be a 2nd screen experience providing opportunities for interactive activities that aren't possible within the live feed itself. Will the 2nd screen experience be fixed in the spherical VR world or move when the end-user turns his head? How will the end-user interact with it? Much thought, experimentation, and testing will go into this, since UI design can enhance, or detract from, the VR experience.

Sim Sickness

Sim Sickness (Simulator Sickness) is a real problem for some people. Symptoms include eyestrain, headaches, problems standing up (postural instability), sweating, and nausea. It can occur during the VR experience. It can occur as the end-user takes off the display and returns to reality.

To date there is no universally agreed upon explanation for why it occurs. Possible causes include; a) cue conflict - a mismatch between what we expect to see and feel and what we are actually seeing and feeling, and b) postural instability - our body relies on accurate sensory input to constantly make small adjustments to not fall over, and VR provides powerful unfamiliar sensory input.

Technology-based and artistic choices can be used to minimize the risk of inducing Sim Sickness. These include; maintain high frame rates and low latency, avoid flicker, match sensory expectations, and limit uncontrolled movement (i.e. remember that the camera is the end-user's head. People see stable images, not shakey handheld camera shots).

Blogger Ben Lewis-Evans wrote an excellent introductory primer[15] on Sim Sickness. Oculus regularly updates a Best Practices Guide[16] articulating technical guidelines

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[14] One example of this research is reported in VIRTUAL NOSE KEEPS GAMERS FROM FEELING SICK, Purdue Univ., March 30, 2015, http://www.futurity.org/virtual-nose-video-games-nausea-886692/?utm_source=Futurity+Today&utm_campaign=3fbd6152da-March_30_20153_30_2015&utm_medium=email&utm_term=0_e34e8ee443-3fbd6152da-203925913

[15] Simulation Sickness and VR - What is it, and what can developers and players do to reduce it?, Ben Lewis-Evans, April 4, 2014, http://www.gamasutra.com/blogs/BenLewisEvans/20140404/214732/Simulation_Sickness_and_VR__What_is_it_and_what_can_developers_and_players_do_to_reduce_it.php

[16] Oculus Best Practices Guide, January 2015, http://developer.oculusvr.com/best-practices

for experience design to minimize the risk of inducing Sim Sickness. The U.S. Army Research Institute for the Behavioral and Social Sciences produced a rigorous Introduction to and Review of Simulator Sickness Research[17] in April 2005.

Close

This paper has focused on live VR. Computer-rendered VR opens up even more questions and choices. How is the participant's journey directed through the story when they have free will? How can blocks of narrative be remixed to yield satisfying narrative experiences? How is time managed? How does the end-user interact with the created world (ex. rules and acceptable behavior)? Is some control given up in "story-telling" in order to allow the user to participate in "story-making"?

Everything about VR is evolving rapidly. We are currently inventing the tools and assembling the language of this new artform. The vast majority of our potential audience does not have first-hand experience with VR. We are starting to identify what works for us – the insiders – but we don't yet know what works in them – our audience. Some of the specific products mentioned in the paper may be obsolete by the time it is published. But as we have seen from cinema, TV, and games, when we get the art 'right,' it will persist, evolve, and be embraced.

Philip Lelyveld runs the VR/AR Initiative at the USC Entertainment Technology Center. He recently brought communities of hands-on practitioners together to discuss and document the current states of 'the emerging language of VR storytelling' and 'live VR production workflow.' Phil also consults on product strategy and business development to CE multinationals and startups. He can be reached at PLelyveld@ETCenter.org

[17] www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA434495

Sidebar – Camera options for shooting live VR

Ricoh Theta (https://theta360.com/en/about/theta/) is a candy-bar size device with two back-to-back 180 degree cameras. It can shoot up to 3 minutes of spherical video with sound. The image is stitched in non-real time. This is not a streaming VR device. The Theta app allows for playback on IOS, Android, and Windows smart devices using finger-swipe and gyroscope control of the 360 image. It also plays back in Google Cardboard and other phone-based VR headsets. (MSRP $299.95)

Giroptic (http://www.giroptic.com) is a sealed unit of 3 cameras that can shoot 360 degrees by 150 degrees vertical and fits in the palm of your hand. It shoots equirectangular streaming 30 fps video footage at 2K resolution (2048 x 1024), and still images at 4K (4096 x 2048). The file format is mp4 / h264 for videos and jpg for pictures The unit records on battery for 30 minutes and is water resistant down to 10 meters. The Light Bulb adapter (220/110 volt compatible) provides direct power to the 360cam, enabling full speed wifi connectivity to the local network. (Available for pre-order. MSRP $499.)

360fly from EyeSee360 (http://eyesee360.com) will shoot 1504 x 1504 video at 29.95 fps (H.264) using eight ultra fisheye lenses. (Shipping August 2015. MSRP $399)

BublCam (http://www.bublcam.com) is a 3.14" diameter sphere with 4 cameras, each with a 190 degree field of view (FOV). The camera has a 2 hr battery life and is capable of HDR and time-lapse. Video is captured in MP4 / H264, with audio in MP3. Resolution varies by frame rate and selected FOV. Full tech specs are available on the website. BublCam offers real-time stitching software for streaming VR. Bubl Xplor App (mobile app) and Bubl Cloud (web app) enable capture, upload, view and share to windows, iOS, and Android devices. They call the three viewing options Touch (finger swipe), Tilt Pan (wave the tablet around), and VR Pan (view in a phone-based VR viewer). (Backordered. MSRP $799.)

Ladybug (http://www.ptgrey.com/360-degree-spherical-camera-systems) from Point Grey Research, is a family of cameras that capture from 75% (Ladybug2) to 90 percent (Ladybug5) of the visual sphere. Ladybug5 captures 30 MP (5 MP x 6 sensors) at 5 FPS uncompressed or 10 FPS compressed JPEG. Ladybug5's post-processing workflow provides maximum dynamic range and user flexibility by moving the image processing from the camera to the host PC. Users are able to make decisions and experiment with settings post-recording and watch the effects in real-time; no need to re-record. The Ladybug systems use software to calibrate each camera on its own and in relation to each of the other five cameras. The system is able to know the vector associated with every pixel, in each camera, to one-hundredth of a degree accuracy.

Jaunt (http://www.jauntvr.com/#about) is a one-stop end-to-end VR production solution vendor. They offer a variety of VR camera configurations as well as 3D sound field microphones. Two of their camera configurations are a 16- or 20-GoPro camera integrated disk. Stitching and computational 3D is performed using Jaunt's proprietary algorithms. They are working on their own cameras for greater reliable

and higher resolution than the GoPros currently built into their rigs. On June 30th Jaunt announced Neo, a professional-grade 360-degree VR camera system.

GoPro (http://gopro.com) is currently the most common camera used for consumer and prosumer VR. 360 Heros (http://www.360heros.com) and Freedom 360 (http://freedom360.us) are two of the leading GoPro VR camera mount vendors. They offer a variety of camera mounts for different camera counts and use cases, including 3D. GoPro bought Kolor (http://www.kolor.com), a leading video stitching software vendor.

Lucidcam (http://www.lucidcam.com) is a 180 degree 3D handheld camera with spatial audio. Put two Lucidcams back-to-back for 360 degree coverage. As of this writing it is not yet on the market, although there are demo videos on the website.

Jump (https://www.google.com/get/cardboard/jump/)is a VR solution developed jointly by Google and GoPro. Sixteen GoPro Hero4 cameras sit in a ring mount. The video is uploaded to the Google cloud, where it is stitched and posted to YouTube. The 360 video is viewable on Google Cardboard and other phone-based VR viewers as well as via touch and tilt-pan on phones and tablets.

Samsung Beacon (http://thinktankteam.info/beyond/), an integrated 16-horizontal (eight 3D pairs) plus 1-vertcal camera disc rig, was shown in November, 2014 as part of Samsung Project Beyond. It isn't an actual product with a release date or price.

Immersive Media (https://immersivemedia.com/) is an end-to-end VR production solution house. They have two camera models, the Hex and Quatro. The Hex camera has six lens. It records a 12 MP 360° video image of 80% of a sphere at 15 fps (5400 x 2700 pixel resolution).

Panocam (http://www.panocam3d.com) offers head mounted and tripod mounted VR cameras. Their head mounted HMC 3D 360 contains 24 synchronized cameras, and captures full panoramic 360 3D at 120 fps.

Fraunhofer Ominicam (http://www.hhi.fraunhofer.de/departments/vision-imaging-technologies/products-technologies/capture/panoramic-uhd-video.html) uses 10 HD cameras pointing vertically at a ring of 30-degree forward-tilted mirrors to create a 10K x 2K 360 image.

NextVR (http://www.nextvr.com) has developed a custom “lens-to-lens” system for capturing and delivering
live and on-demand virtual reality experiences in true broadcast quality. Their camera rig options include a six RED 6K camera rig (3 stereo pairs) capturing at 80 fps. The rig also captures the 3D geometry of the location.

HypeVR’s (http://hypevr.com) virtual reality rig consists of 14 Red Dragon cameras and Velodyne’s HDL-32E, which provides the ability to simultaneously capture all fourteen 6K Dragons at up to 90fps and a 360 degree point cloud at 700,000 points per second.