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CHAPTER 30

EXTENDED REALITY (XR) ENVIRONMENTS

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1 INTRODUCTION

Moore's law, the observation that the number of transistors in an integrated circuit doubles approximately every two years, has become an almost ubiquitous metaphor for the rapid pace of innovation in any number of technical domains. Unpacking this metaphor, one could easily argue that advances in any single technical domain are enabled by a range of contributing factors that extend well beyond the four walls of the laboratory. Changes in social and cultural attitudes, shifts in policy, the elasticizing of borders, and boundaries—both real and perceived—across private and public as well as commercial and non-commercial spaces, all combine with scientific and technical innovation in unique ways to lay the foundation for these rapid advances.

eXtended Reality (XR), a technical capability that offers a range of computer-generated immersive experiences that mirror reality to varying degrees, provides an excellent example of how advances across many different domains continue to drive innovation—and in turn, open up new avenues of application. The basic requirements for developing effective XR solutions—hardware, software, and user-centered design (UCD) principles—remain unchanged since as far back as the "Link Trainer" (Jeon, 2005) or Morton Heilig's "Sensorama" (Heilig, 1962). Yet, understanding the biological and cognitive processes underlying human perception, memory, and action; extent to which the core technologies have become smaller, more powerful, and more readily available; and, degree to which designers, developers, and users are now able to interact collaboratively in real time, have combined to place XR at a tipping-point of becoming a common-place tool for training and educating, collaborating and partnering, networking and entertaining, and other applications which have yet to be envisioned and realized.

This chapter provides an overview of advances in five specific areas that collectively empower XR to branch into the very fabric of our everyday lives, professionally, socially, and personally. The chapter begins with a perspective on the technology, providing an overview of the basic system requirements for XR, discussing how advances in hardware, software, and related capabilities continue to enable ever more realistic and immersive experiences—and make them available to an increasingly larger and broader audience. The chapter then shifts to the perspective of the user, focusing on how UCD principles can and should be

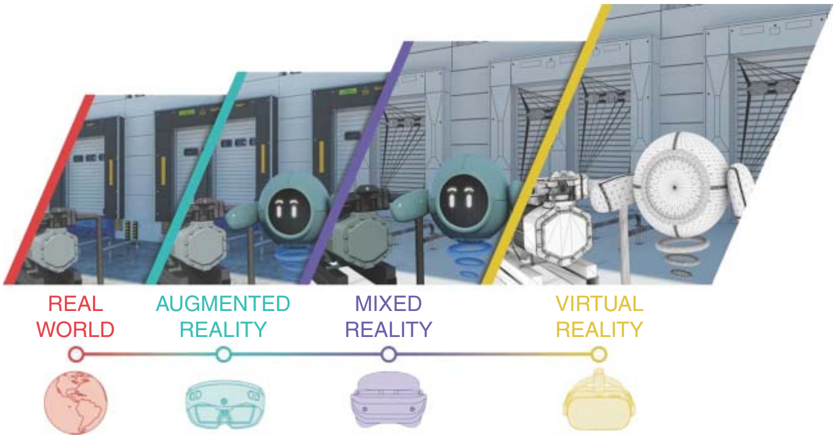

Figure 1 Virtuality continuum.

applied to maximize the immersive experience while minimizing perceptual dissonance. The chapter then moves to specific issues affecting the utility and use of these systems—and how to manage them—focusing on health, safety, and social concerns. The chapter ends with a review of several different domains for which XR is readily suited.

2 SYSTEM REQUIREMENTS

eXtended Reality solutions are computer-generated immersive environments that provide a spectrum of experiences (see Figure 1), including (Mann, Furness, Yuan, Iorio, & Wang, 2018; Milgram & Kishino, 1994):

- Augmented Reality (AR), which overlays virtualized content onto the real world;
- Mixed Reality (MR), which in addition to augmenting the real world with virtualized content, allows the virtual content to be aware of and interact with the real world; or vice versa with real objects in a virtual world, i.e., Augmented Virtuality (AV), which is another form of MR;
- Virtual Reality (VR), which fully immerses users in an entirely simulated virtual world;
- XR Blended, which is the *blending* of all three form factors, including the point-of-need overlays of AR, immersive contextualization of VR, and physical interaction afforded by MR, to achieve a currently unparalleled immersive experience.

Advances in powerful hardware chipsets, such as mobile multicore Central Processing Units (CPU), Graphics Processing Units (GPU), and even artificial intelligence (AI)-dedicated neural chipsets, have made possible the high frame rates and performance necessary to create seamless experiences across this virtuality continuum (Milgram, Takemura, Utsumi, & Kishino, 1994). Advances in tracking technologies have seen expensive, bulky external sensors now being integrated into headset technology itself. Improvements in software and hardware allow these tracking technologies to maintain refresh rates necessary to seamlessly correlate virtual and real-world imagery, thereby providing an engaging immersive experience (see Table 1). Increasing battery life, mobile bandwidth, and app ecosystem compatibility, coupled with decreasing data latency, price point, and social inertia are collectively providing the foundation for mass adoption of XR solutions (Cook, Jones, Raghavan, & Salf, 2018).

System requirements for XR solutions include hardware tools consisting primarily of:

- interface devices, oftentimes head worn, used to present multimodal information and sense the XR world;
- interaction technology that allows users to navigate through and interact with the XR world;
- tracking devices used to identify head, hand, and limb position, orientation, and location.

And software tools including:

- modeling software to develop 3D models, which constitute XR content assets;
- developer software used to generate XR content;
- communication networks used to support multiuser XR experiences.

2.1 Hardware Requirements

XR experiences require higher-end hardware as compared with traditional PC or mobile software experiences (Xoticpc, 2019). For non-XR applications, high-end requirements generally require "gaming" hardware capable of rendering realistic virtual imagery and auditory cues at real-time frame rates of 30 frames per second (FPS) or greater. With XR, however, additional concerns must be accounted for. In XR, 30 FPS is not acceptable, as any frame rate less than 60 FPS can break immersion and even render users sick, with 75 FPS or greater preferred (Oculus, 2017). In addition, typical PC or mobile software experiences only render to a single display device, such as a monitor or TV. While this is true for monocular based-AR on mobile devices, stereoscopic head-worn displays (HWDs) have two displays, typically at HD resolution, that must render the virtualized imagery at 60 FPS or greater, effectively doubling the workload of the GPU. Additionally, XR tracking systems, which must be maintained by the CPU at just as high of a refresh rate, are more sophisticated than the traditional mouse, keyboard, or game controller typically associated with high end gaming platforms. While advances in mobile chipsets, such as the Qualcomm Snapdragon XR2 and Apple A13 Bionic, are starting to realize these hefty requirements in mobile platforms and HWDs, many XR platforms are still tethered to high-powered desktop-class CPUs, such as Intel's 10th generation Core Processors, and GPUs, such as the Nvidia's RTX series (Burek & Stobing, 2019).

Table 1 Technology Component Comparison Across XR Platforms

	XR platform		
Component	Augmented Reality	Mixed Reality	Virtual Reality
Environment	In AR, the environment is the real world and virtualized content is overlaid onto the real-world location	In MR, augmented content is overlaid onto the real world, but additionally it interacts with the real world, e.g., a virtualized character walking along a real-world desk	In VR, the environment is entirely virtually simulated via 3D models or 360 video
Hardware	In AR, hardware is typically a mobile device or an HWD that allows for view of the real world. Sensors could be as simple as an RGB camera to a depth-capable camera	In MR, hardware requires some perception of the real world, which needs depth sensing capabilities via a depth capable camera, or advanced computer vision algorithms that can detect real-world planes via a normal camera	In VR, hardware is typically a HWD that occludes the real-world view from the wearer; Sensors for tracking are integrated or external
Interaction	In AR, interactions are done primarily via gestures—touch on mobile, and hand gestures with HWD; and can also include movement and speech. For HWD platforms, head tracking can additionally fuel interaction. Some platforms employ controllers	The interactions for MR are largely similar to AR	In VR, interactions are done primarily with position and/or rotation tracked game-controllers, but also can include gestures, head tracking, movement, and speech
Software	In AR, high frame rates are typical, but the hardware itself is typically self-contained and not as powerful as VR PCs, so visuals are typically not as high resolution	Similar to AR, MR systems are usually self-contained, but additional consideration needs to be given to physics and collision resources for real/virtual interactions	In VR, high frame rates are typical, as many VR platforms are currently tethered to high-powered PCs, they oftentimes also feature high-resolution visualizations

2.1.1 Augmented Reality and Mixed Reality Technology

Augmented reality and mixed reality involve overlaying virtual content onto the real world (Cipresso, Giglioli, Raya, & Riva, 2018; Mann et al., 2018). This is typically delivered spatially and in real time, using either a mobile device such as a smartphone or tablet, or using an HWD. In AR, the visible natural environment is simply overlaid with a layer of digital content. In MR, augmented content is localized and affixed to the real world using either computer-vision-based methods to determine the position of the augmented content, or infrared-based depth sensors that spatially map out the surrounding environment.

Tablet- and smartphone-based AR/MR solutions are often delivered using typical commercial-off-the-shelf (COTS) devices, such as an iPhone or Android tablet or smartphone (Mann et al., 2018). These systems use SDKs, such as Apple's ARKit (see Figure 2) or Google's ARCore, to provide immersive experiences (Shavel, 2018). These solutions work by leveraging onboard camera systems on mobile devices and computer vision algorithms to predict, map out, and track a spatial understanding of the area to be augmented. Because these cameras do not have true-depth mapping capability, the algorithms are optimized to detect vertical and horizontal planes. These planes are then tracked and maintained relative to the camera's position in real time. Developers can then affix augmented content to these planes, and as long as the tracking system is maintained, augmented content remains fixed to the planar anchor. This allows users to either place AR content into the world at a fixed position or extend their AR application into an MR application that actually interacts with the real world, e.g., making a virtualized character that walks around the planar area detected on a real floor.

Advanced tracking AR solutions incorporate localized tracking combined with odometry-based navigation systems, such that pose data (i.e., location and orientation) can be accurately perceived across large distances where GPS data are limited or unavailable (Laney et al., 2019). This capability expands the effective working space for a mobile solution, allowing accurate placement and viewing of virtual objects beyond a single room without the need for excessive fiducial markers—supporting larger indoor spaces than would previously have been known to the AR system. Using this technology, AR systems can build pose data as a user moves throughout an unmapped space, building a "breadcrumb" trace of where they have traveled so that placed AR markers can be viewed accurately at a later time. Applications for this tracking and registration capability include disaster response, underground operations, and indoor navigation and beyond.

For HWD-based AR/MR systems, such as the HoloLens 2 and Magic Leap One, similar spatial mapping algorithms are executed, but are typically more accurate than their mobile counterparts (Brigham, 2017). This is because HWD-based systems are outfitted with infrared depth sensors that can provide a much more accurate spatial mapping system than what can be provided using a simple camera (see Figure 3). These infrared sensors are sometimes colloquially called 'inside out' because the sensors are mounted to the HWD and track the outside world relative to the headset (Cook et al., 2018). This is in contrast to older HWD systems that did not contain sensors, such as the Canon MREAL, that required mounting infrared sensors to the HWD and externally, in a fixed area such as a 10×10 room, tracking the HWD position. The more modern 'inside out' sensors allow users to escape the restrictions associated with sensor- and camera-filled rooms.

Figure 2 Floor and desk horizontal planes detected using ARKit.

Figure 3 HoloLens spatial mapping overlaid onto a real-world space.

HWD systems are typically outfitted with high resolution binocular projectors that can render AR/MR content onto a see-through optical display (Cipresso et al., 2018; Mann et al., 2018). These modern HWDs allow users to see the real world directly rather than through a pass-through camera system. The previous generation video pass-through systems had to integrate both virtual imagery and a camera feed into a single image in real time, which proved to be both costly and demanding in terms of hardware resources, thereby often resulting in a low quality view of the real world, as the view was observed through a digital capture of a camera. Some AR HWD systems, such as the Vuzix M400, provide a monocular rather than binocular display system. While these can be useful to display 2D-fixed information or even images over the real world, without stereoscopic projection capability these systems typically are not used to place augmented content spatially, and function in a way more similar to projection-based heads-up displays (HUDs) than AR devices.

Both mobile- and HWD-based AR/MR systems can use image recognition, also called fiducial markers (see Figure 4),

Figure 4 Fiducial marker being used to anchor a virtual plant to a physical image.

to recognize a particular image and calculate its location, scale, and orientation in real time with respect to a camera's position (Romero-Ramirez, Muñoz-Salinas, & Medina-Carnicer, 2018). This allows developers to affix these markers to particular locations, such as specific pieces of equipment, for accurate anchoring of virtual content to an associated image and subsequent real-world equipment locations.

In addition to affixing augmented visual content to the real world, AR developers can affix spatialized sound (see Chapter 18 by Casali in this volume) to the environment (Bauer et al., 2019). Spatial sound is best instantiated in HWD-based AR solutions, since the primary tracking target for such systems is the user's head rather than a handheld tablet. While, in the past, headphone spatialization required expensive, specialized hardware to achieve real-time rates, modern multicore processors have made it possible to render complex audio environments over headphones. With binaural rendering, a sound can be placed in any location, right or left, up or down, near or far, via the use of a head-related transfer function (HRTF) to represent the way sound sources change as a listener moves his or her head (Meshram et al., 2014). While for optimal results, HRTFs must be personalized for each individual user, fairly accurate generic models are typically provided and perform satisfactorily (Berger et al., 2018). Most of the mainstream AR/MR HWD manufacturers provide optimized sound SDKs, such as the HoloLens' Unity plug-in (Microsoft Spatializer; Microsoft, 2019c), which allow for content developers to implement spatialized sounds whose source is a location in three-dimensional space, or volumetric sound areas, thereby isolating or playing particular sounds when a user enters particular areas of the augmented world.

2.1.2 Virtual Reality Technology

Virtual Reality technology involves simulating an entire virtual world, including assets and the world itself, and presenting that in an HWD such that the users' view and perception of the real world is obstructed (Cipresso et al., 2018; Mann et al., 2018). Similar to AR/MR technology, VR technology involves rendering realistic virtualized imagery in real time to users using advanced hardware. These systems can take three main configuration forms (Greenwald, 2019; see Figure 5):

- tethered to high-powered 'VR-Ready' PCs using headsets, such as the HTC Vive Cosmos, Oculus Rift S, Valve Index, or Windows Mixed Reality (see Figure 5(a));
- tethered to mobile device-driven headsets, such as the Google Daydream, Nintendo Labo VR Kit,

Figure 5 (a) Oculus Rift; (b) Samsung Gear VR; and (c) All-In-One Oculus Quest System.

Qualcomm-Compatible XR Viewers, or Samsung GearVR (see Figure 5(b));

- wireless and self-encapsulated standalone systems, such as the Oculus Quest, Pico Neo 2, Oculus Go, Lenovo Mirage Solo with Daydream, or HTC Vive Focus (see Figure 5(c)).

The tethered VR configurations (see Figure 5(a)) are currently the most powerful form factor for delivering VR solutions. These headsets offload expensive CPU and GPU calculations to modern desktop PCs equipped with multi-core CPUs and GPUs, with high RAM. This allows lightweight headsets to simply contain projection systems and sensor systems to track positions, while offloading heavy lifting computer calculations to the tethered computer's hardware. These systems, however, have the disadvantage of always having to maintain the tether, which is not readily viewable when immersed in a VR environment and can cause users to trip or use less locomotion to explore the virtual world than they would with a tether-less form factor. Further, while these systems do provide 6 degrees of freedom (DOF), the tether makes this cumbersome for users and limits their exploration potential.

The second form of VR configuration consists of a mobile smartphone inserted into a lightweight chassis equipped with binocular optics (see Figure 5(b)). These solutions use local computational resources to interactively render VR content via CPU/GPU on the smartphone (Lai et al., 2017). Since mobile devices are typically not as powerful as desktop PCs, virtualized imagery is typically not as realistic in appearance as compared to other VR form factors. These solutions also lack advanced sensors to track position and only track head rotation, offering 3DOF potential. This limits their use to seated/stationary VR applications and precludes their use for physical locomotion. Another disadvantage of this type of VR headset is its reliance on a mobile device being mounted into the display for the duration of the immersive experience. This can be cumbersome and make scalability and deployment of this type of VR systems difficult since the mobile device is typically an externally obtained smartphone. While these systems are less powerful, of lower immersive quality, and less deployable than their PC counterparts, they do allow users to be immersed in a tether-less VR environment, which can provide usability advantages. At the time of this writing, however, the Google Cardboard, Google Daydream, and Samsung GearVR smartphone VR platforms appear to be phasing out (Greenwald, 2019).

The final VR configuration form is self-encapsulated systems (Greenwald, 2019; Robertson, 2019; see Figure 5(c)). These "all-in-one" headsets contain all necessary CPU, GPU, and tracking hardware in one system. While they are slightly heavier than their tethered counterparts, they are still lightweight and designed for prolonged periods of use. These systems are also easier to set up because they are not bound to a specific room or PC setup. They also provide 6DOF wireless tracking in real time. A disadvantage of these systems compared with desktop VR systems is that they do not have as extensive CPU and GPU capabilities, so if ultra-realistic imagery is important for a particular VR application, the tethered form factor is likely most suitable. Also, the battery life on self-encapsulated systems tends to be a limiting factor, although they can be run continuously while tethered to a power adapter.

2.1.3 Interaction and Tracking Technology

While previous generation computer systems used a mouse, keyboard, or game controller, current XR systems afford a large variety of techniques for interaction. Interaction in XR is typically accomplished using one or a combination of the following methods:

- gestures
- controllers
- head tracking
- movement
- speech

Gesture recognition is one of the primary forms of interaction in XR. Gesture recognition is the process by which human position and movement are tracked and interpreted to recognize semantically meaningful gestures (Turk, 2014). Gestures can be used to specify and control objects of interest, direct navigation, manipulate the environment, and issue meaningful commands. In the past, gesture tracking devices were worn (e.g., gloves, bodysuits) but significant advances have been made with passive techniques (e.g., computer vision), which provide more natural, non-contact, and less obtrusive solutions than those that must be worn. These advances have extended into AR mobile and headset environments. For example, the Magic Leap One and HoloLens 2 headsets provide full real-time hand tracking and gesture recognition (Stein, 2019). VR headset manufacturers, such as Oculus and HTC, also are integrating hand tracking into some of their platforms. Apple's ARKit 2 provides real-time body tracking without the need for obtrusive suits, sensors, or a wired PC (Lang, 2019a). Currently, however, hand-gesture models and libraries are not uniform across platforms, which presents usability problems in terms of learnability, memorability, and ease of use (Case, 2019). There is a need to standardize gesture interaction in XR platforms, just as WIMPs (windows, icons, menus, pointing device) standardized interaction in Windows-based applications.

Controllers are another form of interaction used in XR (Case, 2019). Unlike past controllers that simply consisted of buttons and analog sticks, XR controllers are outfitted with sensors that allow for some form of tracking in 3D space. On the lower end, these can be simple 3DOF controllers such as the Oculus Go's controller, which allows users to "point" their controller at virtual content and interact with it, to advanced 6DOF controllers, such as the HTC Vive or Oculus Touch controllers. While 3DOF XR applications tend to render the virtual controller alone, 6DOF XR applications often render hands in place of the virtual controllers or hands with virtual controllers (XR Association, 2019). The more advanced 6DOF controllers provide real-time position and rotational updates that have a low enough latency and accurate enough tracking to allow for the creation of a new generation of full body interaction, such as that used in the fast-paced game *Beat Saber* (Lang, 2019b). Controllers are more predominately found on VR platforms. For AR mobile platforms and AR headsets, controllers are typically secondary to gestures, although depending on the manufacturer they may offer a controller across the 3DOF to 6DOF spectrum.

XR HWD platforms typically offer 3DOF or 6DOF head-tracking (Lang, 2013). 3DOF head-tracking tracks the rotational movements of the head but cannot track locomotion, such as walking forward and backward or standing up and sitting down, which is typically true of lower-end and mobile VR platforms and some AR headsets, such as the Epson Moverio BT series (Greenwald, 2019). Other HWDs offer 6DOF head-tracking, such as the Oculus Quest and Microsoft HoloLens 2. These solutions allow users to interact with augmented content by using their head. For example, an AR application could require a medical trainee to move their head close to a virtualized patient's mouth to teach students how to position themselves to check for proper breathing.

6DOF HWDs also enable movement and locomotion, which is another form of interaction. With the advent of inside-out tracking and portable wireless computer systems in all-in-one XR HWDs, such as the Magic Leap, Microsoft HoloLens, and Oculus Quest (Greenwald, 2019), users can now easily move through immersive environments, whether VR or AR. Even when using fully occluded VR platforms, users can safely traverse an area that contains obstacles. This is made possible by "boundary systems" present in many VR platforms (Dingman, 2019). These systems allow users to map out boundaries around real-world obstacles prior to being fully immersed in the virtual world. These obstacles include such items as couches and coffee tables, walls in the room, or anything that could prove hazardous to users. Once all obstacles are defined, the boundary box becomes invisible, allowing users to roam freely and safely in the virtual world (see Figure 6). If users approach one of the boundaries, a virtual representation of the obstacle is overlaid, providing a cue to users that they've reached the limit of the occupiable real space. Typically, at this point users can either turn around and go back into their current virtual/real-mapped space, or they can use a mechanism typically dubbed 'teleportation' to designate with an input device (typically a controller) where they would like to teleport to in the virtual space. The virtual world's frame of reference is then teleported to that location, which provides users a new location in the virtual/real-mapped space that allows them to traverse the desired area. This type of system is realized, for example, in the Oculus Guardian System (Oculus, 2019).

Another interaction option is speech control. Google (Google Developers, 2019), Apple (Martinmitrevski, 2018), and Microsoft (2019c) all have sophisticated speech recognition libraries available for developers to integrate into XR applications. These systems typically work best with pre-programmed keywords, but also contain dictation engines that can process large volumes of verbalized speech into interactions that can be processed in real time and deployed into XR applications. These dictation engines, however, often require internet access for processing, which may or may not necessarily be possible in all locations where XR systems are deployed. This presents a challenge if text input is used in place of speech, which can be highly cumbersome in XR platforms.

To support natural and intuitive interaction, a variety of interaction techniques can be coupled. For example, combining speech interaction with nonverbal gestures and motion interfaces can provide a means of interaction that closely captures the way we interact with the real world.

2.2 Software Requirements

Software development of XR systems has evolved from traditional backgrounds of both game development, as well as computer programming. In a unique way, both of these once similar but separate fields have now been combined to create realistic XR worlds driven by sophisticated back ends that

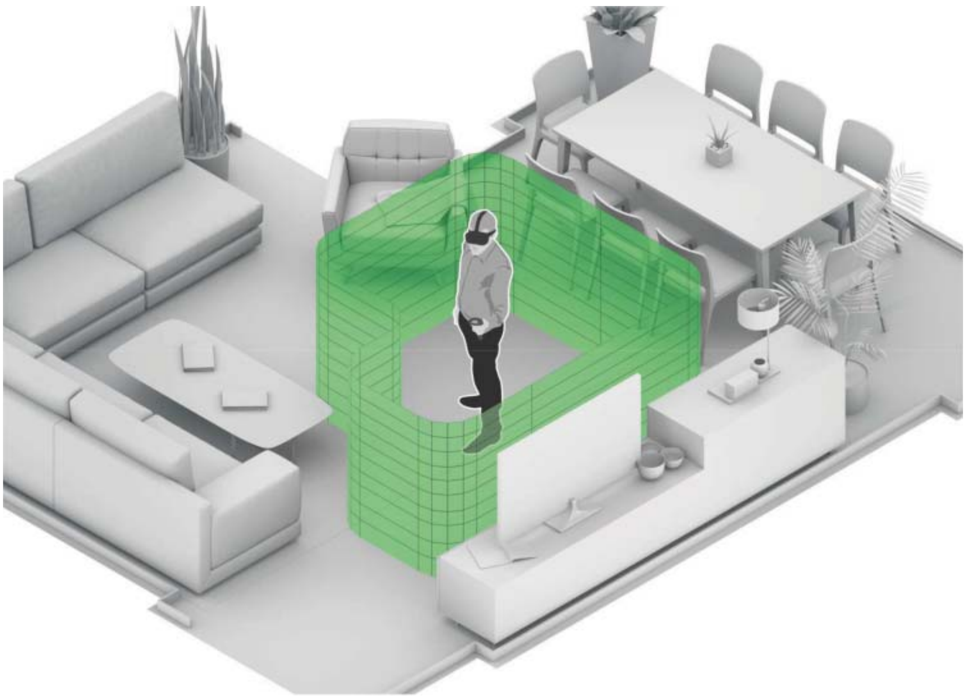

Figure 6 Boundary box.

model realistic data (e.g., biological processes associated with a given anatomical system in a medical XR training system; Sadeghnejad et al., 2019). Integrated Developer Environments (IDEs), such as Unity3D and Unreal, initially developed for game developers have now become the primary platforms for development of XR content (Unity, 2019). XR Standards, such as OpenXR by Khronos Group (Orland, 2019), are being developed to make cross-platform XR development more simplified and streamlined. Primers are also evolving to guide XR application development (XR Association, 2019).

Software development of XR systems involves creating 3D models to represent the virtualized world and augmented content to be rendered, developing software code to drive the state and behavior of the virtual world and its content, and then deploying these assets onto XR hardware platforms that may be hosted by ultra-broadband networks (Cook et al., 2018).

2.2.1 Modeling for XR

Modeling XR worlds and their associated content has evolved from the creation of 3D models optimized for CAD or post-processed computer-generated imagery used in films, to those that are optimized for real-time rendering at high FPS in order to maintain immersion and avoid causing cybersickness (Caserman, Martinussen, & Göbel, 2019; Cook et al., 2018). Thus, content may need to contain relatively low polygon counts and texture sizes in order for XR systems to maintain acceptable rendering rates, even on higher end hardware. These 3D models are commonly created with COTS tools, such as 3DS Max and Maya (Gaget, 2019), and come in a variety of formats, such as FBX (Filmbox) and OBJ.

Exciting advances are on the horizon, which promise a more specific XR-oriented portable 3D model format. Two such formats now available are known as USDZ (Universal Scene Description) and glTF (Graphics Library Transmission Format) (Ramamirtham, 2018). USDZ, which was developed by Apple and Pixar, allows developers to make 3D models in the traditional manner, but additionally provide real-world scale and other factors specifically optimized for XR. These USDZ models can then be downloaded directly onto an XR device and presented in the real world, maintaining their scale and position once placed. glTF provides an efficient, interoperable format that minimizes the size of 3D assets, as well as the runtime processing needed to unpack and use those assets in real time.

2.2.2 Software Development for XR

Although the sophistication of XR applications can vary from very detailed and immersive VR solutions to AR applications that consist of only overlaying simple 3D modeled content onto the real world, most XR applications require software engineers to develop interactive content (XR Association, 2019). This typically involves importing 3D models into an Integrated Development Environment (IDE), such as Unity, and exercising software engineering development skills to bring the content to life. To assist software developers, SDKs have been developed that are optimized for XR and provide low-level tools and functionality needed to develop XR applications. Typically, aggregate libraries that support multiple platform specific SDKs, such as Apple's ARKit and Google's ARCore, are wrapped into collective SDKs such as Unity's AR Foundation, which allows software developers to target both platforms with the same code. Exclusive features to specific platforms are still available and engineers can properly architect their code to take maximum advantage of specific platform capabilities, while creating a common code base for common XR functionality. For example, Microsoft's Mixed Reality (MR) Toolkit is a popular SDK that at face value targets Microsoft's products, but this SDK is actually designed to be platform agnostic and XR device independent (Jackson, 2018). This allows developers to take advantage of MR Toolkit's large library of XR interactions and XR user interfaces. A developer could, for instance, use MR Toolkit to develop an AR application for HoloLens, Oculus Rift, and even tablet-based AR platforms by using ARKit and only write minimal additional code to support all three form factors.

After 3D content is developed and the software has been written to drive that content, the final step is deploying the content to the different XR platforms. For desktop XR applications this involves creating a simple executable that is run like any normal application. These executables can be delivered to clients using a variety of methods (physical or digital delivery) and, provided the required XR hardware is available, clients will be able to run these applications in the same manner as any other desktop application. For mobile-based AR, such as iOS and Android, XR applications may need to be prepackaged into a store-delivery format and then submitted to the device's respective store. Store-based AR apps typically require additional instructions due to the wide variety and availability of deployment and to avoid confusion for users who may be unfamiliar with XR technology. Human interface guidelines are available to assist developers in making the transition to XR easier and more intuitive for users (Apple Developer, 2019; XR Association, 2019).

2.2.3 Networks

XR developers need 10–20x the storage capacity as compared to requirements for playing traditional standard HD video files (Cook et al., 2018). Cloud XR services can help meet some of these requirements by allowing for processing of XR-related content to be delegated to significantly more powerful server PCs rather than handled locally on mobile devices and HWDs. This can mean significant battery and CPU power savings, which leads to longer XR content usage, and more local resources dedicated to other tasks, such as improved content fidelity. Cloud XR services also allow for unique synchronization of content across multiple devices and multiple users. For example, Microsoft Azure's Spatial Anchors allow content to be anchored and persisted in the real world (e.g., a park playground) and then consumed on other AR devices (Microsoft Azure, 2019). This is the backbone of the game *Minecraft Earth*, which allows players to augment the real world with virtualized Minecraft worlds using their AR-enabled handheld smartphones or tablets (Minecraft, 2019).

While many urban areas are now outfitted with high-speed fiber optic internet connectivity from the hundreds of Megabits to even Gigabit per second (Gbps) range, there is great promise in wireless connectivity in the near future obtaining similar or even faster speeds with the advent of 5G, which boasts theoretical speeds of up to 20Gbps (Qualcomm, 2019). Combined with its wireless connectivity and intended integration into mobile devices, internet speed may present a much less or even mitigated bottleneck in the propagation of XR Cloud services in the near future.

3 DESIGN AND IMPLEMENTATION STRATEGIES

While many conventional human–computer interaction techniques can be used to design and implement XR systems, there are unique design and implementation considerations that must be addressed. In particular, given the multi-space realm of XR applications, users need to be provided with natural and intuitive designs that are ubiquitous with their environment.

Designing for the goal of UCD will first inform the types of user activities and behavioral responses from the system that need to be created. Then, specific XR design principles can be considered to ensure naturalistic XR interaction is achieved. In particular, designers must consider the appropriate spatial and behavioral interactions, conversation, multi-space, navigation and wayfinding guidance, and spatialized auditory information design principles that will lead to the creation of an engaging experience that promotes presence and immersion, while minimizing cybersickness. XR design principles and guidelines are ultimately focused on taking advantage of the multi-dimensionality of XR in such a manner that a user-centered, intuitive, engaging, and non-sickness-inducing immersive experience is realized.

3.1 User-Centered Design in XR

The goal of UCD for immersive XR environments is to create a solution that is ubiquitously effective and engaging for target users. In *The Design of Everyday Things*, Don Norman states a ubiquitous design derives from "an approach that puts human needs, capabilities, and behavior first" (1990, p. 8). These basic principles for UCD need to be carefully instantiated in XR applications if these solutions are to reach mass adoption. Specifically, *the first phase of XR-specific UCD* is to analyze the target context of use including users, goals, tasks, and environments (de Clerk, Dangelmaier, Schmierer, & Spath, 2019) to determine if there is justification for immersing users in an extended reality. When a user is technologically engulfed in and surrounded by a vivid, multi-sensory alternative reality that transports them away from their physical reality, it is known as *immersion* (Witmer & Singer, 1998). Immersion may lead to *presence*, which is a subjective psychological experience of actually "being" in an alternative reality. Key benefits of immersion and presence relate to XR's more realistic spatial cues (e.g., stereopsis, motion parallax) that support higher levels of spatial understanding as compared to standard, non-immersive displays (Ragan, Sowndararajan, Kopper, & Bowman, 2010), as well as the ability to take advantage of physical, whole-body interactions such that one can either virtually (VR) or physically (AR) embody perception and manipulate content in 3D space (Johnson-Glenberg, 2018). Results are mixed with regard to whether or not these immersive benefits enhance learning, with some studies demonstrating enhanced human performance with higher levels of immersion (Bowman & McMahan, 2007), while others suggest there may even be an adverse effect on human information processing (see Chapter 5 by Wickens and Carswell in this volume), perhaps because of distractions from the real world (Oh, Herrera, & Bailenson, 2019). Thus, before adopting an XR solution, it is important to determine if an immersive environment is appropriate.

Once immersion has been determined to make sense for a given application, *the second XR-specific UCD phase* is to derive the requirements of use in order to determine which type of immersion is most appropriate, as VR and AR/MR systems offer different experiences.

In VR, users are transported to and completely immersed in a virtual environment (see Figure 7). For VR, there needs to be justification for over-riding the real world (e.g., cost, safety, inaccessibility, etc.). For example, a specific training environment that is out of reach physically or too dangerous to directly train in could be reproduced in VR in order to match the operational environment (Champney, Carroll, & Surpris, 2014). For instance, Walmart's diversity, inclusion, and situation VR trainer provides a well-suited use case, as it allows trainees to experience non-typical situations (e.g., Black Friday, discriminating situations with fellow employees/customers) and to practice their reactions without having to recreate the situation at a larger scale or with live actors (Akhtar, 2018). Another use case is the application of VR in treating phobias. Studies have found successful treatments of spider phobias when users confronted their fears in the virtual world (Miloff et al., 2019). After receiving this treatment, participants experienced significant reductions in behavioral avoidance and self-reported fear. In general, VR is expected to fill use cases in the areas of entertainment and video games (Burt, 2019), social networking and collaboration (Cook et al., 2018), manufacturing design (Mamiit, 2016), employee training (Sonalkar et al., 2020), education (Markowitz et al., 2018), therapy (Bailey et al., 2017;

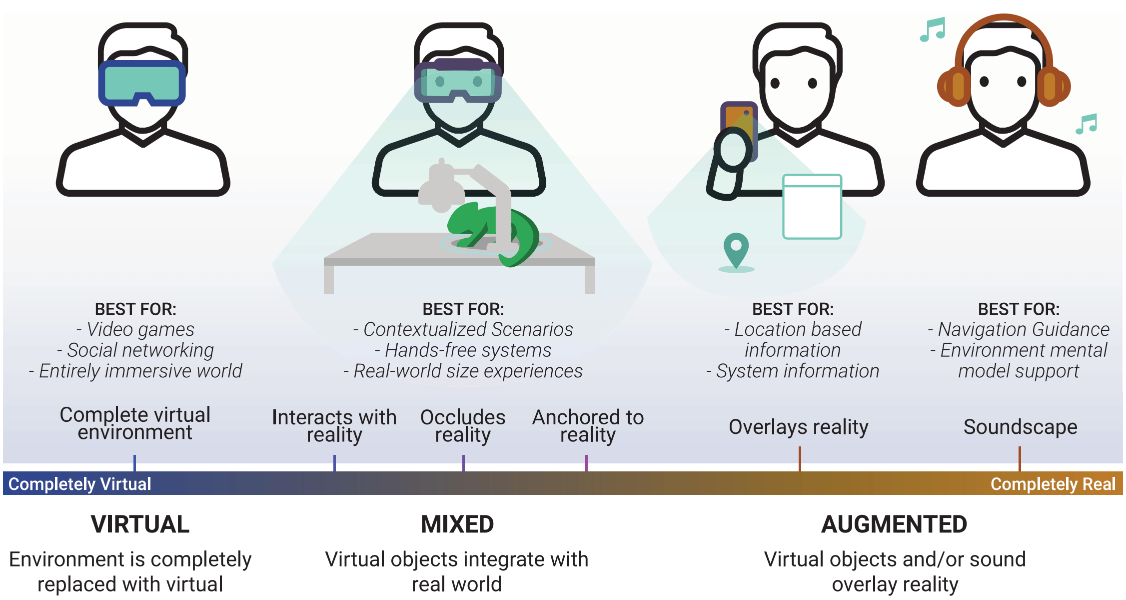

Figure 7 Virtuality continuum in context.

Bullock et al., 2019; Rizzo, 2019), rehabilitation (Koenig, Krch, Lange, & Rizzo, 2019), customer interaction support (Akhtar, 2018), and more.

In MR, users remain in the real world and non-real, virtual sensory information, such as sound, video, graphics, haptics, and olfaction, is "smartly" overlaid onto the real world, thereby allowing users to physically interact with and manipulate both real and virtual items and environments (see Figure 7). A primary benefit of MR is that it can provide contextually anchored information, which allows the system and user to react based on the context of the real world. GPS location, environmental surfaces, real-world textures, and real-world objects all provide contextual channels to information (Ajanki et al., 2011). Thus, MR alters and adds to what one perceives in the real-world environment, allowing users to interact hands-free in contextualized scenarios and at real-world scale. For instructional applications that do not require simulated environmental factors for training (e.g., a large-scale accident, a fire, or other virtual contexts that are difficult, dangerous, or costly to recreate in the real world), MR provides the opportunity to engage with real-world objects in augmented space, walking around, interacting with, and physically exploring and learning from both the real world and augmented entities. This was possible for doctors at Cleveland Clinic who, after teaching anatomy in MR, saw a significant increase in recall and performance compared to those who did not receive MR training (Akhtar, 2018). Overall, for onsite assembly support, safety operations support, and process manufacturing, and other forms of hands-on training, which benefit from contextualization of information, embodiment of actions and hands-free operation, MR technology is a strong use case (International Data Corp., 2017).

In AR, location-based digital content is overlaid on users' real-world surroundings in real time to inform or guide (see Figure 7). AR can enhance everyday experiences by aiding perception (see Chapter 3 by Proctor and Proctor in this volume), comprehension, and interaction with the real world. Lowe's Home Improvement utilized the contextualization that AR offers after they identified a pain point with their customers: the inability to commit to remodeling without seeing the outcome. Their AR application allows users to preview virtual options overlaid onto a physical showcase kitchen. This left users feeling confident in the product and informed about their decision (Akhtar, 2018). Overall, in pre-purchase situations (e.g., "trying on" clothes before going to a store; International Data Corp., 2017), retail showcasing (e.g., foreseeing how a living room would look with new decorations; Dacko, 2016), experience augmentation (e.g., visitors of a museum viewing digital information [history, opinions, etc.] or hearing soundscapes (Janer, Roma, & Kersten, 2016; Sikora, Russo, Derek & Jurčević, 2018) superimposed onto exhibits they are viewing), assistive technology (e.g., supporting day-to-day affairs, such as navigating public transportation; Oesterreich & Teuteberg, 2018), and process manufacturing job aids (e.g., putting a device into location to show how it fits into an overall mechanism; de Souza Cardoso, Mariano, & Zorzal, 2019; Palmarini et al., 2018), which benefit from contextualization of 2D and 3D animations, vivid instructions/information, and ability to annotate, AR technology is a strong use case.

While a primary benefit of both VR and AR/MR is that they allow users to have virtual embodiments, which enhances both ease of user interaction and presence, particularly by providing an anchor for visuomotor tasks (Borrego, Latorre, Alcañiz, & Llorens, 2019), they do so in different ways and thus one must carefully determine which form of embodiment meets the needs of a given XR application (Matamala-Gomez et al., 2019). In general, there are three specific subcomponents that can create a sense of embodiment: sense of self-location, sense of agency, and sense of body ownership (Kilteni, Groten, & Slater, 2012) (see Figure 8).

- *Sense of location* (i.e., a sense of residing inside a body) can be fostered by providing a first-person visual perspective.
- *Sense of agency* (i.e., a sense of being able to initiate and control actions) is fostered when users are able to interact with and control their movements in active XR scenarios, especially when they are pursuing a goal and there is a possibility of achieving that goal through

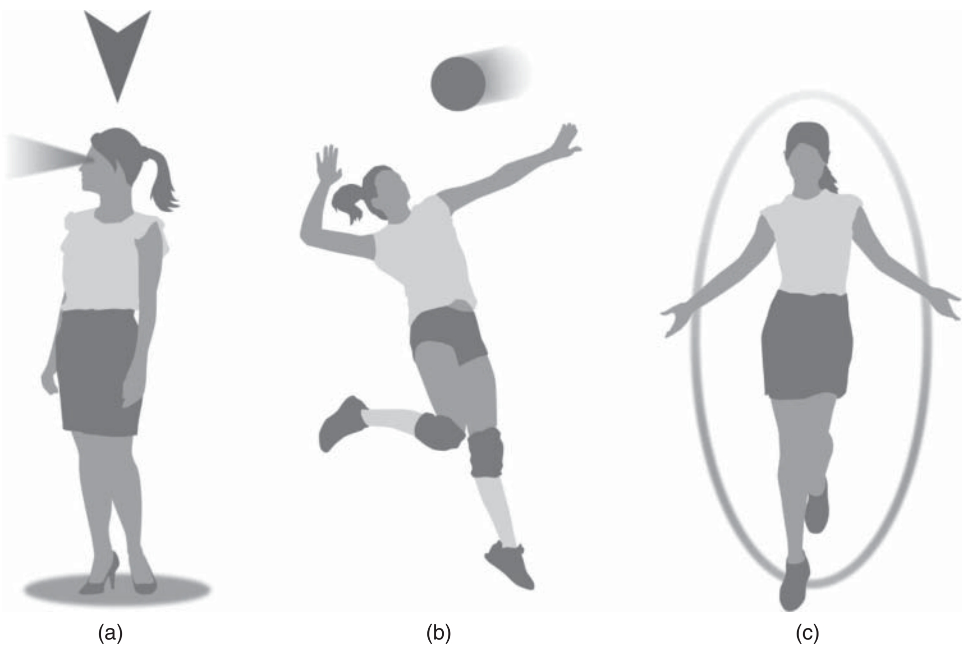

Figure 8 Three components of embodiment: (a) sense of location; (b) sense of agency; (c) sense of body-ownership.

self-directed physical movement even though their body is not physically in the virtual space (Gorisse, Christmann, Houzangbe, & Richir, 2019; Piccione, Collett, & De Foe, 2019).

- *Sense of body ownership* (i.e., a sense of self-attribution of a body) can be fostered by increasing the sensory correlations between the actual physical stimulation of one's biological body and the visually seen stimulation of an avatar's body (see Chapter 29 by Duffy in this volume) or body part and ensuring the avatar's body obeys structural and morphological constraints such that it appears human-like (Braun et al., 2018).

In VR, embodiment is generally achieved by using a self-avatar to represent and replicate a user's body posture and motions using body-tracking systems (Gonzalez-Franco & Lanier, 2017; Spanlang et al., 2014). Lee (2004, p. 376) explains that "In the case of a psychologically assumed virtual self … a virtual environment reacts to users as if they were in there." While in VR, the real body is dissociated from the virtual representation, embodiment can be effectively achieved for given body parts by factoring in the three components: (1) first-person visual perspective; (2) being able to initiate and control actions; and (3) mapping users' physical movements to avatar actions, as much as possible. For example, Gilbers (2017, p. 46) demonstrated "the possibility to experience ownership over a third virtual hand, as more than 25% of the participants (in their study) experienced that they had three hands." VR-based embodiment is most appropriate when users need to experience presence and body ownership. A user's sense of location can be altered when they are provided a rich environment to experience and create a dynamic viewpoint for themselves; "Embodiment performs a spatial narrative of the landscape and the story" (GitHub, 2020). Body ownership of a different persona allows a user to gain perspective due to: (1) the emotional connection that is built when inhabiting a different body; and (2) experiencing the virtual world react to the user's actions while embodying a different being. Body ownership can build strong feelings that can affect intrinsic motivation.

> *If one feels embodied in a virtual body, insults or praise regarding this body, referring to properties that would not be true for the biological body, could cause emotional arousal … one would manifest strong reactions to a threat in the case where it refers to one's own body, compared to when there is no sensation of ownership.*
>
> (Kilteni et al., 2012, p. 382)

In AR/MR, embodiment (Rosa et al., 2019) is generally achieved by allowing users to see their real body and providing virtual hands, extended bodies, or extra limbs when interaction occurs outside of personal space (Cutting & Vishton, 1995). Embodiment in AR/MR is most effectively achieved by: (1) providing users with control of virtual and real objects. Users are more engaged when their actions impact the environment, as "overlapping of cause and event creates a substantive relationship … thus establish[ing] a greater awareness of the role of the body … producing a more intuitive and intimate experience" (GitHub, 2020); (2) using sensors to track the position of user's hands in relation to virtual objects, thereby enabling users to pick up virtual objects, manipulate them, and move them about. This embodied interaction with virtual content has been demonstrated to enhance learning (Santos et al., 2014). Further, presentation of virtual objects and real-world elements must be choreographed in such a manner as to create interactions that best determine when users need to have their hands/body visible within the field of view versus when AR/MR elements should be the prominent view; (3) designing content at proper scale, where AR scene content is rendered exactly where it would be in the physical world to real-life size and depth, encourages users to explore and experience spatial and temporal concepts, provides a means of emphasizing contextual relationships between real and virtual objects, and provides intuitive interaction via a contextually valid dynamic, first-person point of view. Interactions at real-world size/scale can help to create a physical mental model of user actions, such as the optimal embodied manner to complete a task. It is important to note that 'scale' is a multi-dimensional construct and involves design consideration across personal (within arm's reach), action (within 30 m), and vista (beyond 30 m) spaces (Cutting & Vishton, 1995).

Thus, XR exists on a spectrum, where on one end is the real environment and on the other is the completely virtual. Connecting the two ends, augmented reality transitions into mixed, with the biggest contrast being the overlay to anchoring of virtuality onto reality.

The third XR-specific UCD phase is to apply design principles that ensure immersive design solutions satisfy requirements of use identified in the first two phases. UCD principles for AR/MR versus VR experiences vary to some degree.

AR/MR-specific design principles include:

- create a reality enhancing system—one that is "transparent and more a part of the users' perceptive system than a separate entity in itself" (Nilsson, 2010, p. 147);
- consider AR/MR technology and user's limited field of view in relation to their space; ensure users have enough room to properly view augmented content;
- determine critical versus non-critical information and display these information elements with a correct amount of obscurity/opacity.

VR-specific design principles include:

- minimize cybersickness within VR by providing active viewpoint control, reducing sensory conflicts, providing leading indicators, and providing rest frames (Stanney, Fidopiastis, & Foster, 2020);
- consider the 360 environment and provide appropriate visual and spatial audio cues to define distance (Loyola, 2017; Rana, Ozincar, & Smolic, 2019);
- provide boundary markers (see Figure 6) to ensure user safety within the real environment (Dingman, 2019; Hartmann, Holz, Ofek, & Wilson, 2019).

General immersive design principles include:

- rely on sound to provide a well-rounded, situated, and spatially oriented experience, (Janer et al., 2016; Sikora et al., 2018), as when there is a congruence between visual and auditory stimuli users experience a heightened sense of presence (Hruby, 2019), are more adept at navigation (Bormann, 2005), and more effective at search and other such tasks (Rumiński, 2015);
- consider user's field of view and understand perceptual limitations (e.g., distortion due to the structure of the environment and its interaction with augmentations; issues associated with headset field of view, resolution, display size, and contrast; content capturing issues such as image resolution and capture frame rate; issues with the design, layout, and registration of content and augmentations; issues associated with users and their ability to perceive and interact with the virtual world; Kruijff, Swan, & Feiner, 2010);

- provide natural interactions that mimic real life by creating intuitive affordances, as intuitiveness relies on experiences with the physical environment (e.g., using our hands to directly manipulate virtual objects). Pay special attention to the degree of indirection (i.e., spatial or temporal offset between interaction elements and manipulated objects, seeking minimal offset), degree of integration (i.e., ratio of degrees of freedom of task elements versus their input devices, seeking a 1:1 ratio), and degree of compatibility (i.e., correspondence between physical actions of user interactions and those of manipulated objects, seeking direct manipulation; Poor et al., 2016).

Other design considerations for this UCD phase will be considered in Section 3.2, XR Design Principles.

The *fourth XR-specific UCD phase* is to carry out an evaluation to ensure resulting designs are effective, intuitive, and satisfying to use, without causing undue adverse discomfort during use or adverse aftereffects upon post-exposure. Gabbard (1997) developed a taxonomy of usability characteristics for immersive environments, from which Stanney, Mollaghasemi, Reeves, Breaux, and Graeber (2003) developed the MAUVE (Multi-Criteria Assessment of Usability for Virtual Environments) approach, which organizes usability characteristics into two primary usability attributes (XR system usability and XR user considerations); four secondary attributes (interaction, multimodal system output, engagement, and side effects); and 11 tertiary attributes (navigation, user movement, object selection and manipulation, visual output, auditory output, haptic output, presence, immersion, comfort, sickness, and aftereffects). MAUVE is an inspection method that can be used at various stages in the development lifecycle, from initial storyboard design to final evaluation and testing. Beyond usability, the cost-effectiveness of XR systems should also be evaluated (Wang, Wu, Wang, Chi, & Wang, 2018). With these aspects considered, developers can evaluate if XR technology offers performance and financial advantages over current practices or technologies. This is an essential determination if XR technology is to achieve mass adoption both commercially and in research domains.

3.2 XR Design Principles

Immersive XR environments need to be designed to provide users with engaging experiences that allow for direct manipulative and intuitive multisensory interaction (Bullinger et al., 2001), with the ultimate goal of achieving human–human communication/human–system interaction that is as natural as possible (Reeves et al., 2004). If designed effectively, engagement in such immersive multimodal XR experiences can lead to high levels of situation awareness (SA) and in turn high levels of human performance (Hale et al., 2009); however, multimodal interaction within XR must be appropriately designed to lead to this enhanced awareness. To achieve effective and engaging XR applications, there are several design factors to consider, including: natural interaction design, conversation design, behavior and interaction fidelity, perceptual illusions, multi-space design, navigation and wayfinding design, and spatial sound design.

3.2.1 Natural Interaction Design

To design natural XR interaction, it is essential to consider rules governing integration of multiple sources of sensory feedback. People have adapted their perception–action systems to “expect” a particular type of information flow in the real world (Poor et al., 2016); XR runs the risk of breaking these perception–action couplings if the full range of expected sensory cues is not supported or if it is supported in a manner that is not contiguous with real-world expectations. Such pitfalls can be avoided through consideration of the coordination between sensing and user command and the transposition of senses in the feedback loop (Stanney, Samman, Reeves, et al., 2004; Stone, Bisantz, Llinas, & Paquet, 2009). Specifically, command coordination considers user input as primarily monomodal and feedback to the user as multimodal. Designers need to consider (Wickens, Hollands, Banbury, & Parasuraman, 2016):

- which input modalities are most appropriate to support execution of a given task within the XR environment (e.g., time-sensitive information is best presented auditorily, while spatial information is best presented visually);
- how these modalities can be supported (e.g., either directly or via perceptual illusions) and where that support should occur (e.g., focal or ambient);
- if there is any need for redundant user input (e.g., add redundant audio cues to reduce visual demands);
- whether or not users can effectively handle such parallel input.

Further, cross-modal integration rules can be used to consider aspects of multimodal interaction, including (Johnson-Glenberg, 2018; Stanney et al., 2004; Storms, 2002):

- temporal and spatial coincidence to ensure natural perception of perception–action couplings;
- working memory capacity to ensure users are not overwhelmed by the demands of interaction;
- intersensory facilitation effects (e.g., a visual display enhanced by the addition of an auditory display) that can enhance perception in XR environments;
- congruency in associated sensorimotor areas (i.e., intuitive match between design of feedback from different modalities);
- inverse effectiveness (i.e., multisensory inputs interact synergistically when the unimodal stimuli occur at relatively the same time and place and are relatively weak).

Additional multimodal design guidelines have been provided by Hale et al. (2009), who have outlined how a number of sensory cues may effectively be used to enhance specific SA components (i.e., object recognition, spatial, temporal) within an XR environment, with the goal of optimizing SA development.

Multimodal interaction design guidelines continue to evolve and offer techniques to enhance the user experience of immersive XR environments (cf. Almeida, Teixeira, Silva, & Ketsmur, 2019), including perfecting the design of fundamental XR interaction use cases (Ravasz, 2016):

Role of ground. Users must be able to relate to and have a sense of orientation within an immersive XR environment, thus the ground-to-horizon relationship is critically important (Gibson, 2015). In VR, a fixed horizon can provide such orientation, while also reducing cybersickness (Prothero & Parker, 2003). In AR, interaction with virtual objects is affected by their perceived distances, which may be biased if these objects are not perceived as making contact with the ground plane (Rosales et al., 2019). Thus, for AR it is beneficial to use shadows and interreflections (i.e., light reflecting from an object’s surface to the ground surface) to provide cues regarding whether or not an object is in contact with the ground or other support surface.

Atmosphere. Providing aerial or atmospheric perspective (i.e., using color changes to create the illusion of depth by simulating atmospheric hue changes at different distances) can support users in scaling an XR environment, thereby making the experience feel more intuitive and natural. Specifically, objects in action or vista space (Cutting & Vishton, 1995) would have more air and particles to look through to view them, making these distant objects look less sharp and blurrier than close objects (Goldstein, 2013). In general, gradually fading the landscape from personal to vista space provides a clear cue for depth and distance.

Terrain features. Systematically using terrain features, including ground, path, obstacle, barrier, water margin, brink, step, and slope (Gibson, 2015) as the building blocks of an XR environment will result in a natural and intuitive interaction design guided by human intuition.

Approach to the environment through soundscape. Users can be gently immersed into an XR environment through the use of an ambient soundscape that helps the user to build a mental model of the environment before being fully immersed into it. Further, in XR environments, the way sound propagates should be altered by the structure of a space, its architecture, textures, and general organization, thus directing how a space is perceived (Herzer, 2014; Janer et al., 2016; Sikora et al., 2018).

Wayfinding with objects. Although having an XR environment cluttered with a bunch of virtual elements might break user's immersion, such objects can be highly effective in guiding users through the environment if they are contextually relevant (e.g., users can be guided via directional AR prompts overlaid onto the real-world setting to guide them to the most efficient route). In general, egocentric-updating of location is crucial for navigating and wayfinding in unfamiliar environments, and immersive XR environments can facilitate this process through the provision of prominent features (e.g., landmarks, well-structured paths, regions with varying sensory characteristics, signs at decision points) present along the route (Sharma et al., 2017).

Contextual reticle. To orient users in space, a contextual reticle can be used to show the center of focus, direct gaze, and support movement and interaction with objects. Different states of the user, such as idle state, movement state, and interaction state demand different interactions from the reticle.

Interactive objects. When users are in the XR environment, interactive objects should draw attention with subtle changes, such as with minor shading in the color of the object or even a subtle sound depicting its behavior, or with the help of a contextual reticle.

3.2.2 Conversation Design

Conversation and existing voice user interfaces are a good fit for XR systems, particularly for AR, given the hands-free capabilities that voice interaction can provide and the desire for 'reality-based' interaction (Girouard, Shaer, Solovey, Poor, & Jacob, 2019). With the multimodal capability of XR systems, a "say what you see" convention can help guide users to say the correct prompts and constrain user input (Yankelovich, 1996). Voice is an efficient input modality, allowing hands-free interactions; in contrast, visuals are an efficient output modality, allowing presentation of a vast amount of information at the same time, which in turn reduces the burden on users' memory (Whitenton, 2017). Google's (2020) conversation design guidelines outline how to build a VUI (Voice User Interface), which requires designing a persona that can represent a familiar entity while providing natural communication based on the user. Coined by Grice in 1975, the cooperation principle is a natural form of communication in which both participants in a conversation are believed to want to cooperate (Grice, 1975). This is a helpful standard when creating sample dialogs. After creating a persona, Google's conversation guidelines recommend drafting sample conversations between the persona (system) and user to experiment and inform component driven prompts. Scripts can follow the process of natural conversation turn-taking: User utterance, persona situation identification, persona response, and persona conversational turn ending prompt. For advanced systems, components may include several variants to structured dynamic, rule-based sentences. Effective principles for conversation design include:

- rely on existing models of human-to-human conversation when designing conversations;
- anticipate and build the system to understand multiple user utterances, including providing feedback for those utterances;
- limit the amount of information provided to users to avoid information overload and user frustration, providing no more than three different options per interaction. Group together a longer list and prompt users to explore more options if necessary (via voice response).
- provided that a screen is not available, inform users of functionality that they are currently accessing;
- similar to natural conversation, avoid technical jargon to help reduce cognitive load;
- provide sequential numbering of results, to act as verbal "handles," from which users will easily recall and select;
- create effective and memorable interactable words for users;
- after a persona has responded, set a response time limit that, once reached, creates another response prompt to verify if users still want to continue the conversation.

Following these design standards, conversation design in XR can allow users to comfortably speak and know what to say intuitively.

3.2.3 Behavior and Interaction Fidelity

Studies have shown that in XR, the critical key to creating a realistic experience is to provide object and cue recognitions that are based on familiar behaviors that users can understand. Behavior fidelity can be created by designing reactions of familiar objects and cues to follow real-world physics, gravity, and optical laws (Jerald, 2015). Behavior fidelity of objects can be realized in XR according to (Maier & Fadel, 2009; Poor et al., 2016; XR Association, 2019) by:

- using physics collisions to indicate interactions between different virtual objects;
- using physics colliders that indicate to users they have moved into an object (e.g., a virtual wall) even if the object is outside of the user's current field of view;
- carefully designing two-handed interactions in XR, as they are difficult to convey unless users' hand representation can be veridical in the virtual world;
- conveying the weight of virtual objects by, for example, providing resistance to the raycast used to select them, such as by having the raycast bend a small amount for light objects and larger amounts for heavier objects, thereby creating the illusion that virtual objects have mass;

- infusing audio into 3D objects and/or adding attenuation to sound effects by allowing the audio to fade and stop when users are no longer interacting with the objects;
- using affordances to subtly communicate the properties of an artifact to afford its potential uses to users.

In addition, interaction fidelity (i.e., action realism, wherein users have the ability to directly control and manipulate the XR environment) can be created by designing user actions in XR to resemble real-world actions in terms of biomechanical similarity, input, and control. Guidelines for interaction fidelity include (Rogers et al., 2019):

- provide high interaction fidelity to support object manipulation tasks in XR;
- provide moderate interaction fidelity for whole-body movements in XR, as abstractions that reduce physical demands or intricate movement may increase usability and ease of use;
- provide designs that encourage exploration in XR such that users interact with the virtual space (e.g., novel forms of navigation and orientation; use of search-based game mechanics);
- consider onlooker effects, which can engender feelings of self-consciousness during XR whole-body or, contrarily, decrease feelings of isolation to XR interaction;
- for smartphone- and tablet-based AR, as visual localization of objects can be very dependent on how the device is being held, provide indicators to guide object localization, such as blur, contour scale, or vocal hints;
- for smartphone- and tablet-based AR, provide interactions that consider building for use of two hands and provide clear instructions that illustrate the role of the hands during those interactions;
- consider haptic substitutions, such as tapping two fingers to each other for sensory replication or by providing visual/audio feedback, to increase immersion;
- provide substitutions (e.g., perceptual illusions) and approximations for physically challenging whole-body movements (e.g., holding a button to simulate holding on to a virtual object), which may increase interaction fidelity.

3.2.4 Perceptual Illusions

When sensorial transpositions are used, there is an opportunity for perceptual illusions to occur. With perceptual illusions, certain perceptual qualities perceived by one sensory system are influenced by another sensory system (e.g., 'feel' a squeeze when you see your hand grabbing a virtual object). Such illusions could simplify and reduce the cost of XR development efforts (Debarba et al., 2018; Nilsson, 2018; Storms, 2002). For example, when attending to a visual image coupled with a low-quality auditory display, auditory–visual cross-modal perception allows for an increase in perceived quality of the visual image. Thus, in this case, if the visual image is the focus of the task, there may be no need to use a high-quality auditory display.

There are several types of perceptual illusions that can be used in the design of XR environments (Debarba et al., 2018; Nilsson, 2018; Steinicke & Willemsen, 2010):

- visual illusions can be used to replace missing proprioceptive and vestibular senses, as vision usually dominates these senses. For example, vection (i.e., a compelling illusion of self-motion throughout a virtual world) is known to be enhanced via a number of display factors, including a wide field of view and high spatial frequency content (Hettinger, 2002), moving sounds (Riecke, Väljamäe, & Schulte-Pelkum, 2009), and viewpoint oscillation (Kim & Khuu, 2014; Kitazaki, Onimaru, & Sato, 2010).
- change blindness (i.e., failing to notice alterations in a visual scene) can be used to apply subtle manipulations to the geometry of a virtual world and direct movement behavior, such as redirecting a user's walking path throughout a virtual environment (Hartmann et al., 2019; Suma et al., 2010);
- acoustic illusions (e.g., a fountain sound; Riecke et al., 2009; Riecke, 2016) could be used to create a sense of vection in an XR, even when no such visual motion is provided;
- haptic illusions (Collins & Kapralos, 2019; Hayward, 2008) could be used to provide users with an impression of actually feeling virtual objects when they are in fact touching real-world props or traveling along a trajectory path that may even vary in size, shape, weight, or surface from their virtual counterparts without users perceiving these discrepancies (e.g., feel an illusory bump when actually touching a flat surface (Robles-De-La-Torre & Hayward, 2001); feel an illusory sharp edge when hand actually travels along a smooth trajectory (Portillo-Rodríguez et al., 2006)).

One solution to current technological shortcomings, sensorial transposition, occurs when a user receives feedback through senses other than those expected, which may occur because a command coordination scheme has substituted available sensory feedback for those that cannot be generated within a virtual environment. According to Stiles and Shimojo (2015), cross-modal mappings are ubiquitous and include such things as the intuitive matching of high frequency sounds to vertically elevated locations, scan time to horizontal/left-right coordinates, brightness to loud sounds, and the very basic more to up/less to down. Such multimodal mappings may be critical to ensure sensory substitution devices are intuitive.

Sensorial substitution schemes may be one-for-one (e.g., visual for force) or more complex (e.g., visual for force and auditory; visual and auditory for force). If designed effectively, command coordination and sensory substitution schemes can provide multimodal interaction that allows for better user control of XR environments. On the other hand, if designed poorly, these solutions may in fact exacerbate interaction problems. Some design principles to consider when implementing sensorial substitution schemes include (Kristjánsson et al., 2016):

- ensure sensorial substitution schemes only convey critical information to avoid overloading human information processing (see Chapter 5 by Wickens and Carswell in this volume);
- ensure sensorial substitution schemes are tasks-focused, as bandwidth differences between sensory systems severely constrain the nature and amount of information that can be conveyed;
- consider more than one sensory feedback modality, as the design of multisensory integration may not necessarily be confined to one source of feedback;
- assess the nature of spatiotemporal continuity for different senses, as perception is a continuous process (see Chapter 3 by Proctor and Proctor in this volume) and thus sensorial substitution schemes must consider how perception changes over time.

3.2.5 Multi-Space Design

Designing for a multidimensional space has been an artform for decades. Whether layering a painting (i.e., with a foreground, mid-ground, and background) or creating forced perspective on a theater stage (i.e., as developed during the Italian Renaissance, where principles of perspective allow designers to create vistas with objects decreasing in size toward a "vanishing point" on the horizon, such as conveyed via a proscenium "picture frame" stage), the foundation for the design of space and depth has evolved over time. Cutting and Vishton (1995) suggest three separate spaces around a moving observer that are important to layout and distance based on their ordinal depth-threshold functions, including personal space, action space, and vista space. In virtual XR spaces, design principles can be created specifically for these three separate, user interaction spaces (see Table 2).

Personal space is described as the "zone immediately surrounding the observer's head, generally within arm's reach and slightly beyond" (Cutting & Vishton, 1995, p. 100). When immersed in an XR environment, users will perform the bulk of their interactions within this space. In the real world, this surround is typically regarded by a user as their "own" space and is portable, morphing in terms of size and proportion as one interacts with the environment (Sommer, 1969). The same must be achieved in XR spaces if they are to be natural and intuitive. Thus, within an XR environment, personal space should not be designed as a passive "out there" structure; it should be created to support a complex and dynamic exchange in which the virtual space informs human knowledge and affords user interaction, thereby shaping the manner in which users come to know the virtual space. Some principles by which an authentic personal space can be achieved include:

- Design visual cues carefully as they are critical in perceiving personal space, including (from most critical to least) occlusion, binocular disparity, relative size, accommodation and convergence, and motion parallax generated by head movement and manipulation of objects (Cutting & Vishton, 1995). It is important to note that depth order from occlusion can rely on contrast and on fine details (as low as 1 arc min), which may not be perceivable at certain sizes and distances, thus needing to be altered depending on the XR HWD (Rolland, Ha, & Fidopiastis, 2004). Navigation cues are also important in personal space, specifically as they relate to guiding users in where to orient their heads such that their FOV is positioned to take in priority information.
- As our bodies contribute to the perception of what is real (Lakoff & Johnson, 1999), for personal space to be perceived as authentic it is important to foster embodied perception. This can be achieved by integrating many senses into the design of user interactions, such as touch, positional awareness, balance, sound, and movement through which an embodied knowing of complex behaviors can be derived within the virtual space (Wilson & Golonka, 2013).
- Consider experiential qualities of virtual spaces in addition to visual properties, such as the ability of the body to "read" the environment via haptic cues, which can be derived by requiring users to move through space, engage with it, and have memorable physical experiences along the way (Lyndon & Moore, 1994), as well as providing a feeling of heat and humidity, momentum of gait and body inertia as one traverses a virtual or augmented space, and echo of footfalls, all of which convene to define tactile resilience of place-form (Frampton, 1983);
- Foster spatial stability (Dessing, Crawford, & Medendorp, 2011), despite continuous changes in sensory and motor inputs owing to movement of eyes, head, and body, to foster haptic understanding (O'Neill, 2001);
- Avoid locking UI elements into the corners of an XR headset, rather, position content either in 3D space with a body-locked behavior (tag-along) or in a world-locked position (Microsoft, 2019a). Such UI elements are a type of information source that can support interaction in personal and action space (see Table 2).

Table 2 Information Source Types Within Areas of XR Space

	Personal space	Action space	Vista space
Occlusion, interposition	X	X	X
Relative size	X	X	X
Motion parallax/ perspective	X	X	
Height in visual field		X	X
Ariel perspective			X
Texture gradients			X
Accommodation and convergence	X		
Binocular disparity, stereopsis	X		
Contextual cues	X	X	X
Navigation cues	X	X	X
Boundary area		X	

It is essential that personal space be designed to accommodate action. If a user is situated in a location that does not accommodate action, the system should automatically identify such physical limitations within this space and recommend the user move to a better location before beginning the experience (i.e., a feature many VR games offer today). This type of contextual cuing from the real-world environment is useful within personal space because of the ability to detect the real world and notify the user of physical space requirements.

Action space extends from the end of personal space to about 30 m—"Because the utility of disparity and motion perspective decline to our effective threshold value of 10% at about 30 m … this effectively delimits space at 30 m" (Cutting & Vishton, 1995, p. 101). Within this space, users can walk and run. Dreamworks suggests in their VR Storyboard Convention model that this is the space narrative occupies. The mobility of users suggests that it is critical to provide area boundaries in this space to avoid physical collision. In addition, in this space, cues that must carefully be designed are occlusion, height in the visual field, motion perspective, and relative size, however, the small field of view and low resolution of many XR HWDs may compromise some of these cues. Accommodation, convergence, and binocular disparity cues within an XR HWD will likely not support human depth perception in action space. Some of the principles by which an authentic action space can be achieved include:

- Use an invisible "boundary system" to map out action space, including boundaries around real-world obstacles so users can be warned if they are about to collide with an object or have reached the limit of the occupiable real space (Dingman, 2019; Hartmann et al., 2019; XR Association, 2019). XR headsets, such as the HoloLens, can provide spatial mapping to assist in boundary creation.

- Use subtle contextual cues to help set user expectations for how far they can roam within action space, such as by using a virtual floor that changes material or texture, fog that gets denser as users roam toward the edges of active space, or grid lines that show the actual boundaries of action space (Hartmann et al., 2019; XR Association, 2019).
- Support object manipulation within action space (Poor et al., 2016; XR Association, 2019) by doing the following:
  - Set maximum placement distance defaults to help ensure users place objects at comfortable viewing distances, have objects maintain realistic scale as users drag them around the action space, provide visual indicators for user's awareness about system-interpreted user gaze (e.g., raycast), and use visual indicators for destination points (e.g., shadows) to help users understand where objects will be placed on a detected surface.
  - Anticipate proximity as an attempt by users to interact with objects. If a user makes a gesture in proximity of an object, consider providing feedback regardless of the type of gesture.
  - Provide virtual objects with surface detection so that objects don't appear to be levitating.
- Given the amount of likely movement in action space, provide users with micro navigation (i.e., fine adjustments needed to orient users to desired location) cues that do not obscure the environment.

Finally, vista space is beyond 30 m from users. Daum and Hecht (2009) suggest that vista space should be divided into near vista space (i.e., up to 100 m) and far vista space (i.e., >100 m) because underestimation and spatial compression in near vista space are expected to be roughly proportional, whereas in far vista space overestimation and expansion of the visual field are typically over-proportional; thus, different design principles are needed in these sectors. Vista space is a limited interaction zone, wherein perspective of imagery should replicate the real world. Occlusion, texture gradients, height in the visual field, relative size, and aerial perspective (Cutting & Vishton, 1995) are several cues that can be utilized in this space to build critical depth information, however, field of view and HWD display resolution may compromise the effectiveness of these cues. Contextualized spatial audio in this space can serve as a helpful cue to indicate distance and provide subtle world building information. Some principles by which an authentic vista space can be achieved include:

- Similar to a painting, provide aerial perspective by replicating differences in color and opacity that occur naturally from the atmosphere to help users intuitively understand variations of distance (Cutting & Vishton, 1995).
- Based on the amount of effort that users may perceive a vista space to impose, consider changes in terrain to achieve realism. For example, if users are tired, they may perceive a path up a hill to be a longer distance (Daum & Hecht, 2009).
- Consider how weather, color, and type of terrain can be used to affect distance estimation for users. "Soldiers tend to underestimate distances when the targets are clearly visible, the air is clear, the sun is at their back, or the terrain is not fully visible or uniform" (Daum & Hecht, 2009, p. 1129).
- Consider how global landmarks within vista space (such as hills and skyline) can be used to provide spatial knowledge to users, helping to enrich their cognitive map (cf. Minocha & Hardy, 2016).
- Avoid placing critical information in vista space, as difficulty in translating information in vista space can cause misinterpretation (National Research Council, 1997).
- Given the amount of likely movement in vista space, provide users with macro navigation (i.e., selecting routes over long distances) cues that do not obscure the environment.

3.2.6 Navigation and Wayfinding Design

To support interaction in multi-space XR environments, it is essential to carefully design for navigation and wayfinding. Effective XR interaction design can be impeded if navigational complexities arise. Navigation is the aggregate of wayfinding (e.g., cognitive planning of one's route) and physical movement that allows travel throughout a virtual environment (Darken & Peterson, 2002). A number of tools and techniques have been developed to aid wayfinding in virtual worlds, including maps, landmarks, trails, and direction finding. These tools can be used to display current position, current orientation (e.g., compass), log movements (e.g., breadcrumb trails), demonstrate or access the surround (e.g., maps, binoculars), or provide guided movement (e.g., signs, landmarks) (Chen & Stanney, 1999). For example, Burigat and Chittaro (2007) found 3D arrows to be particularly effective in guiding navigation throughout an abstract virtual environment. A number of principles concerning how best to design and use navigation and wayfinding tools in XR have been developed (cf. Minocha & Hardy, 2016), including:

- Within smaller XR environments, ensure navigation design takes into account the proximity of users to physical and virtual objects, as field of view limitations within the HWD can present significant issues for micro-navigation.
- Provide bottom-up spatial cues that increase user navigation, such as those provided by an omnidirectional attention funnel (Biocca, Tang, Owen, & Fan, 2006).
- Progressively disclose navigation, to avoid information overload.
- Depending on users' information-seeking goal (locating vs exploring), provide users with information that is specific to their tasks (e.g., for locating tasks, avoid extraneous information that can confuse users; for exploring tasks, provide information about possible areas to navigate to).
- Consider use of virtual landmarks to improve familiarity of surroundings for users, helping to solidify orientation (Foltz, 1998; Minocha & Hardy, 2016).
- For path providence, create semi-translucent route paths instead of directional arrows to eliminate ambiguity.
- In systems where users' SA is a priority for location based interactions, use a World-in-Miniature view in conjunction with AR markers to enhance users' exocentric view (Ball & Johnsen, 2017; Elvezio, Sukan, Feiner, & Tversky, 2017; Stoakley, Conway, & Pausch, 1995).

If effectively applied to XRs, these principles should lead to reduced disorientation and enhanced wayfinding in both large- and small-scale XR environments.

3.2.7 Spatial Audio Design

Audio within XR, as with films and video games, has proven to be important in creating an immersive experience. Schell

(2008, p. 4) explains, "sound is what truly convinces the mind (it) is in a place, in other words, hearing is believing." Spatially, environmental audio cues can live within XR spaces to provide environmental awareness. Placing audio within virtual spaces will allow users to determine the properties of objects and to distinguish location and distance. An example of such a property is when you speak near a wall and feel an echo (Cortes, 2016). For users simply experiencing a soundscape, spatial audio can provide navigation guidance and a mental model support. Microsoft's system, Soundscape, provides users, particularly those with sight loss, 3D spatial audio to enrich their navigation experience (Gartenberg, 2018). Some of the principles by which an authentic spatial audio design can be achieved include (Janer et al., 2016; Sikora et al., 2018):

- Design audio to originate in the appropriate direction to correlate the sound with objects, thus creating binaural hearing to enhance presence (Witmer & Singer, 1998).
- Provide as much haptic information about an object's material as possible via audio. For example, the sound of a metal object interacting with another metal object should make a distinct sound compared to a metal object interacting with carpet.
- When visuals are cluttered or overloaded, provide audio as an alternate solution for information transfer (National Research Council, 1997).
- Audio should contain realistic fall-off curves that model loudness with distance, similar to the real world.
- Provide audio as a source of sensory substitution, particularly for interactions that would naturally require haptic feedback, for example, the click of a button.
- Provide audio cues, such as tones, for communication of simple information and speech cues for more intrinsic types of information (National Research Council, 1997).

3.3 Engagement Design Strategies

Engagement involves both system-driven involvement (i.e., an XR system "provides" immersion) and user-driven involvement (i.e., a user "feels" presence) (Stanney, Mollaghasemi, Reeves, Breaux, & Graeber, 2003). The engagement process starts with the system, as immersion is increased by encompassing users into an XR system with as many relevant multisensory sensations as possible (Mestre, 2005). It is the job of the designed system to keep users in an engagement activity loop, which passes users through activities, accomplishments, and resulting affect by presenting meaningful information for novelty, motivation, and interest. It is during this activity loop that users eventually perceive a sense of presence in the XR environment. Presence has been described as "the psychological perception of 'being in' or 'existing in' the virtual world in which one is immersed" (Mestre, 2005, p. 2) and "as the subjective perception of experiencing oneself as being in a computer-generated environment rather than in one's actual physical location" (Stanney, Salvendy, et al., 1998, p. 459). Presence in XR is valuable because it can reproduce sensation, perceptions, and emotional responses (see Chapter 9 by Feng Zhou et al. in this volume) that are similar to those experienced during human–human interaction (Lombard & Ditton, 1997). Disengagement can happen based on a number of factors (and should be avoided), including: usability challenges, positive or negative affect, perceived time lags and/or interruptions (O'Brien & Toms, 2008), or absence of meaningful information. Some principles by which engagement can be realized in XR include:

- Provide users with meaningful information throughout the system interaction to maintain intrinsic motivation.
- Create challenges that provide an appropriate level of stimulation according to a user's skills and knowledge level; increasing or decreasing as necessary in an adaptive manner (O'Brien & Toms, 2008).
- Provide explanations for system inconsistencies to avoid breaking the suspension of disbelief.
- Encourage perceived user control by providing users with multiple paths to accomplish a goal and control over the inconsequential (O'Brien & Toms, 2008).
- Create a high concept that will provide users with an internal "premise" (story) that sets expectations for system behavior.
- Based on user analysis, provide activities and opportunities that are relevant to users, which will increase likelihood of internal motivation to perform actions.

3.4 Cybersickness Remediation Design Strategies

Exposure to an XR system often produces unwanted side effects that could render users incapable of remaining immersed in the XR environment or functioning effectively upon return to the real world (see Section 4.1). These adverse effects may include nausea and vomiting, postural instability, visual disturbances, and profound drowsiness (Stanney, Salvendy, et al., 1998). As users subsequently take on their normal routines, unaware of these lingering effects, their safety and well-being may be compromised. XR systems and associated usage protocols should be designed to maximize comfort, minimize risks, warn users about potential aftereffects, monitor users during exposure, assess users' risk, and debrief users after exposure. There are design strategies that can be implemented to support cybersickness remediation, such as:

- Provide multisensory feedback that reduces sensory conflicts:
  - Add concordant physical motion to match visual motion (e.g., a motion base) to reduce visual-vestibular conflicts (Bos, 2015).
  - Ask users to actively align their head/body to the behavior of the virtual motion they are experiencing to reduce visual-vestibular conflicts (Wada et al., 2012).
  - Provide users with active viewpoint control by using low latency head tracking (Stanney & Hash, 1998).
  - Provide rest frames from which users can judge virtual motion, with an independent visual background that is in alignment with a viewer's inertial cues likely being a most effective rest frame (Stanney et al., 2020).
- When sensory conflicts cannot be designed out, provide visual motion cues that match users' vestibular system (Prothero & Parker, 2003), such as:
  - A fixed-horizon.
  - A stable vehicle dashboard.
- Provide users with the ability to anticipate impending motion via a leading indicator, which can be created with multisensory cues, including:
  - Visually, such as via a trajectory line that shows the direction of movement, which is a simple but effective visual leading indicator to support movement anticipation (Lin, Abi-Rached, & Lahav, 2004). For example, in *Along the Trail*, a VR application that features a data-generated landscape, users are

provided an orange trajectory line that acts as a 'rail' and is in high contrast against a darker landscape (Panoptic Lab, 2015).
    - Physically, such as via physical leading indicators that are devised to link a passive user's hand (e.g., when a passive passenger) to an active control handle to receive indication of forthcoming motion (Lackner, 2014).
    - Aurally, such as via 3D audio soundscapes or 3D audio beacons and directional audio, that inform users where they are in relation to other locations (Gartenberg, 2018).
- Implement layered teleportation design that combines several unique techniques: peripheral blur, dynamic field of view, blink, and rapid movement.
    - Peripheral blur can be designed to support locomotion. Coined as "teleblur" by Big Immersive (Milik, 2018), such blur can reduce the amount of detail users perceive in their HWD FOV, reducing potential cybersickness triggers driven by visual-vestibular mismatch (Fernandes & Feiner, 2016).
    - Dynamic field of view is a technique by which the HWD FOV is modified based on visual parameters, such as speed and angular velocity, reducing potential cybersickness triggers driven by visual-vestibular mismatch (Fernandes & Feiner, 2016).
    - Blink teleportation is highly effective at eliminating cybersickness because users see minimal motion. With this technique, as users commence movement, signs of motion briefly appear, then the visual scene fades out, and then users are relocated to a new area as imagery fades back in (Neimark, 2019). While this is a successful cybersickness remediation, users are completely taken out of the XR for a significant amount of time, thereby potentially reducing immersion and leading to disorientation.
    - Rapid movement between two location points from a first-person perspective in XR has proven to be successful in maintaining immersion, while significantly reducing motion sickness. Studies found that "rapid movement in very short bursts (<300 ms) doesn't produce any greater feelings of motion sickness than teleportation" (Habgood, Moore, Wilson, & Alapont, 2018, p. 8).

Used together, these cybersickness remediation techniques enhance the XR experience and decrease the likelihood of adverse effects. *Batman Arkham VR* (Kohler, 2016) is an example that utilizes these techniques. When transporting between locations, users experience 400 ms of locomotion coupled with peripheral blur. Once users arrive at their destination, the FOV "blinks" to 90% black opacity and then slowly fades back in. This method of combining multiple remediation techniques offers users several layers of cybersickness protection, while reducing the potential of losing presence.

4 HEALTH AND SAFETY ISSUES

The health and safety risks associated with XR exposure complicate usage protocols and lead to products liability concerns. It is thus essential to understand these issues when utilizing XR technology. There are both physiological and psychological risks associated with XR exposure, the former being related primarily to sickness and aftereffects and the latter primarily being concerned with the social impact.

4.1 Cybersickness, Adaptation, and Aftereffects

Motion-sickness-like symptoms and other adverse aftereffects (e.g., balance disturbances, visual stress, altered hand–eye coordination) are potential unwanted byproducts of XR exposure (Stanney et al., 2020; Stanney & Kennedy, 2008). The sickness related to XR systems is commonly referred to as 'cybersickness' (McCauley & Sharkey, 1992). Some of the most common symptoms exhibited include dizziness, drowsiness, headache, nausea, visual fatigue, and general malaise (Kennedy et al., 1993). The level of adverse effects is more pronounced in VR versus AR/MR.

In VR, more than 80% of users will experience some level of disturbance, with approximately 12% ceasing exposure prematurely due to this adversity (Stanney et al., 2003). Of those who drop out, approximately 10% can be expected to have an emetic response (e.g., vomiting), however, only 1–2% of all VR users will have such a response. In general, those exposed to VR tend to experience more disorientation (D) than neurovegative (N) symptoms, and least of oculomotor-related (O) disturbances, thus having a D > N > O symptom profile (Stanney, Salvendy et al., 1998). These adverse effects are known to increase in incidence and intensity with prolonged VR exposure duration (Kennedy et al., 2000). While most VR users will experience some level of adverse effects, symptoms vary substantially from one individual to another as well as from one system to another (Kennedy & Fowlkes, 1992). These effects can be assessed via the Simulator Sickness Questionnaire (Kennedy et al., 1993), with values above 20 requiring due caution (e.g., warn and observe users) (Stanney et al., 2005).

In AR/MR, users tend to experience less severe adverse symptoms than those exposed to VR experiences (Vovk, Wild, Guest, & Kuula, 2018). This is likely because the real-world provides ample sources that can be used as rest frames from which to judge motion against, thus minimizing the impact of visual-vestibular mismatches between virtual motion of augmented entities and real- world inertial cues. AR displays do, however, still impose vergence-accommodation conflicts, and likely put a physiological load on the human visual system. Thus, in general, those exposed to AR are expected to experience more oculomotor-related (O) disturbances than disorientation (D), and least neurovegative (N) symptoms, with the expectation being that these systems will present with an O > D > N symptom profile, with no dropouts nor emesis (Hughes et al., 2020).

To overcome adverse effects, individuals generally undergo physiological adaptation during XR exposure. This adaptation is the natural and automatic response to an intersensorily imperfect XR and is elicited due to the plasticity of the human nervous system (Welch, 1978). Due to technological flaws (e.g., visual-vestibular mismatches; vergence-accommodation conflicts), users of XR systems may be confronted with one or more intersensory discordances (e.g., a disparity between seen and felt limb position). In order to perform effectively in the XR, they must compensate for these discordances by adapting their psychomotor behavior or visual functioning. Once interaction with XR is discontinued, these compensations may persist for some time after exposure, leading to adverse aftereffects, which pose a safety concern.

Once XR exposure ceases and users return to their natural environment, they are likely unaware that interaction with the XR has potentially changed their ability to effectively interact with their normal physical environment (Stanney & Kennedy, 1998). Several different kinds of aftereffects may persist for prolonged periods following XR exposure (Szpak, Michalski, Saredakis, Chen & Loetscher, 2019). For example, hand–eye coordination can be degraded via perceptual–motor disturbances (Lee & Park, 2019), postural sway can arise (Tychsen & Foeller, 2020), as can changes in the vestibulo-ocular reflex

(VOR) or one's ability to stabilize an image on the retina, and cognitive abilities, such as choice reaction time (Mittelstaedt, Wacker, & Stelling, 2019). The implications of these aftereffects are:

- XR exposure duration may need to be minimized.
- Highly susceptible individuals or those from clinical populations (e.g., those prone to seizures) may need to avoid exposure.
- Users may need to be monitored during XR exposure.
- Users' activities may need to be monitored for a period of time post-exposure to avoid personal injury or harm.
- Design strategies should be implemented that support cybersickness remediation (see Section 3.4).

4.2 Social Impact

eXtended reality technology, like other interactive technologies (e.g., video games, computers), has the potential for negative social implications through misuse, particularly in terms of the possibility for behavioral addictions and hindered social dynamics (Kenwright, 2018). Thailand, Vietnam, China, and South Korea have all instituted shutdown laws that ban young people from playing more traditional online games between certain hours of the day (Király, et al., 2018). The concern is that overuse may cause functional and psychological impairments for gamers, such as impaired interpersonal relationships and decreased work or educational performance (Király, Nagygyörgy, Griffiths, & Demetrovics, 2014). Further, to date, policies that have attempted to address such social issues (e.g., shutdown policies, parental controls, warning messages), have not proven to be effective. The problem is so pervasive that 'Internet Gaming Disorder' (IGD) has been included in Section III of the latest edition of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5; American Psychiatric Association, 2013).

Currently, it is not clear whether or not XR exposure will pose more significant adverse social impacts than its ancestors; early research, however, is not reassuring. Users who engage in what seems like harmless violence in the virtual world experience higher levels of presence and body ownership than more traditional (television) counterparts (Wilson & McGill, 2018), which may desensitize players to violence (Grizzard, Tamborini, Sherry, & Weber, 2017). Thus, XR overuse may pose even more severe concerns than current gaming disorders. Grizzard et al. (2017) found that after playing violent video games for five consecutive days, habituation occurred in that the ability of the game to elicit guilt was decreased with repeated exposure, thereby demonstrating the potential for video game play to lead to emotional desensitization. There is concern that such desensitization to negative stimulation may then subsequently be channeled into real-world activities. Further, what happens if desensitization is coupled with more immersive and embodied XR games; will violent augmented and virtual reality experiences normalize antisocial behaviors (Franks, 2017)? The ultimate concern is that XR immersion may potentially be a more powerful perceptual experience than past, less immersive gaming technologies, thereby increasing the negative social impact of this technology. Further, if societal lines are crossed in XR, its visceral nature may challenge the lines the law draws between virtual, physical, and psychological harm (Lemley & Volokh, 2018). A proactive approach is needed, which weighs the risks and potential consequences associated with XR exposure against the benefits. Waiting for the onset of harmful social consequences should not be tolerated. Koltko-Rivera (2005) suggests that a proactive approach would involve determining (1) types and degree of XR content (e.g., aggressive, sexual); (2) types of individuals or groups exposed to this content (e.g., their mental aptitude, mental conditioning, personality, worldview); (3) circumstances of exposure (e.g., private experience, family, religion, spiritual); and (4) effects of exposure on psychological, interpersonal, or social function.

5 EXTENDED REALITY USABILITY ENGINEERING

Usability engineering involves quantifying experiences of users interacting with systems, with regard to understandability, efficiency, error rates, and user satisfaction (Downey & Laskowski, 1997; also see Chapter 38 by Lewis and Sauro in this volume). The International Organization for Standardization (ISO) has released ISO 9241-11: 2018(en), which defines usability as the "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use," and provides guidance on designing and evaluating human interaction with systems, including regular, ongoing use, infrequent use, learning to use, and maintenance of such systems (ISO, 2019). In addition, the standard aims to ensure a system can be used by people with the widest range of capabilities, while minimizing risks and undesirable consequences of use errors (ISO, 2019). A related standard, ISO 9241-210:2019, *Human-centered Design for Interactive Systems*, focuses on ensuring systems are usable and useful by "focusing on users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques" (p. 1).

More recently, user experience (UX) has emerged as an evaluation field, with a goal of expanding beyond "traditional" task-based evaluations of usability to incorporate a broader scope of metrics that capture dynamic, context-dependent, and subjective indicators of an individual's experience when interacting with a system (Scapin, Senach, Trousse, & Pallot, 2012).

Such multidimensional evaluation approaches are particularly valuable for XR technology, but progress has been slow. For example, according to Dey et al. (2018), less than 10% of AR papers published annually between 2005 and 2014 included a user study. From those that did include a user study, evaluations focused most heavily on user performance (61%) and questionnaire or survey-based findings (50%). Similarly, Cavalcanti et al. (2018) reported that rehabilitation AR usability evaluations lacked heuristic evaluations, and most often focused on task performance (51%), followed by user experience (35%), and few got to the level where perception and cognition were evaluated, which is where many of the benefits of XR are expected to lie (14%). As Dunser and Billinghurst (2011) note, one must go beyond traditional usability methods to provide meaningful evaluations of XR applications, as they are distinctly different from traditional desktop applications. For example, XR systems can support multidimensional object selection and manipulation in 3D space, multimodal system output (i.e., incorporation of visual, audition, and haptics), and collaboration of users sharing the same space. Furthermore, traditional methods do not consider assessing presence and adverse aftereffects, which are of importance in more immersive XR applications (Stanney, Mollaghasemi, Reeves, Breaux, & Graeber, 2003). As XR devices reach mass adoption, there is a need to expand and improve upon evaluation methods to ensure the resultant innovative solutions are highly usable, effective, efficient, and engaging. Usability evaluation of XR systems must thus go beyond the initial focus of task-based assessments to incorporate additional considerations, such as stimulation (i.e., personal growth, increased knowledge and skills), identification (i.e., self-expression, interaction with relevant others), and evocation (i.e., self-maintenance, memories) (Hassenzahl, 2003). Bowman, Gabbard, and Hix (2002) and Ramli and Zaman

Table 3 Usability Evaluation Methods

	Inspection methods: does not require users	User testing: requires users
Qualitative	Heuristic evaluation Cognitive walkthrough	Think-aloud protocols Observation Interviews Focus groups Questionnaires
Quantitative	Performance models (e.g., Fitts' Law; GOMS, KLM)	Formative evaluations Summative evaluations

(2011) provide frameworks for such multifactor usability methods applicable to XR, categorizing methods into qualitative or quantitative, and whether they require users or not. Within these frameworks, the general flow of evaluation activities is: (1) to start with task analysis to understand target tasks and related interactions and information requirements; (2) to follow with expert-directed inspection methods to characterize the specific manner in which XR is being designed to enhance human performance and the user experience; (3) to follow with qualitative user testing to characterize users' thought patterns and perceptions of XR interaction; and (4) finally, to use quantitative—both user-centered formative and comparative summative—evaluations to assess impacts of the XR system in terms of gains in human performance, understanding, and/or user engagement (Gabbard & Swan, 2008). A simplified version of these frameworks is presented in Table 3. This section is organized based on this framework and discusses two main usability evaluation methods: inspection methods and user testing.

5.1 XR Inspection Methods

Inspection methods provide an evaluation of a system against a set of design guidelines (i.e., heuristics) or performance models, which do not require user involvement. In terms of the former, when heuristics are not met, a system is deemed less usable. Often, evaluators set out to complete a set of tasks that represent user interactions with the system (based on a task analysis as mentioned above) and compare each task step to a list of heuristics (also known as a cognitive walkthrough). Violations of heuristics are recorded and submitted back to the design team for consideration and redesign. It is recommended that 3–5 usability experts complete the heuristic review, as little additional information is gained from additional evaluators (Nielsen, 1994). Usability heuristics were first published by Molich and Nielsen (1990), based primarily on desktop computer environments. These were later updated by Nielsen (1994) to generate general guidelines applicable to evaluation of most interactive systems designed for human use. These heuristics, while initially developed prior to prolific use of XR, are applicable to many XR applications due to their general nature. For example, Wang, Cheng, and Guo (2019) found that 77% of 672 issues identified with a function-oriented VR application could be mapped to Nielsen's 10 heuristics.

Many other heuristic lists specific to XR applications have been created over the past few decades in an attempt to capture usability concerns unique to such immersive environments (Altarteer, Charissis, Harrison, & Chan, 2017; Endsley et al., 2017; Gabbard, 1997; Guimaraes & Martins, 2014; Kalalahti, 2015; Ko, Chang, & Ji, 2013; Murtza, Monroe, & Youmans, 2017; Pinelle, Wong, & Stach, 2008; Stanney, Mollaghasemi, Reeves, Breaux, & Graeber, 2003; Sutcliffe & Gault, 2004; Wetzel, Blum, Broll, & Oppermann, 2011). These lists were developed to address aspects of XR interaction capabilities that go beyond usability factors typically related to desktop computing, such as tracking and merging of virtual content and real-world entities in real-time, the need to interact on the go, hand gestures, 3D navigation and wayfinding, immersion, presence, cybersickness, and more. While some provide a manageable list of generalized guidelines (Sutcliffe & Gault, 2004; Murtza et al., 2017), others provide a comprehensive list of issues that are more suitable to application by experienced designers (Gabbard, 1997; Stanney et al., 2003). Table 4 provides a consolidated list of heuristics for XR usability based on previous literature that can readily be applied by evaluators with varied experience.

Beyond heuristics, models of user interaction and human cognitive processing have been developed, which can be used to conduct a predictive analysis of user interaction for a given system design. Fitts' Law describes the relationship between the time it takes to reach a target based on the travel distance and target size (Fitts, 1954). This relationship can be used to design various interaction spaces within XR, ensuring that the speed of movement required is within human capabilities for a given distance and target interaction space size. For example, Fitts's law was applied to investigate effects of geometry displacement and texture rendering on input performance in VR; results failed to show evidence that changing depth cues increased or decreased a user's input performance (Schwind, Leusmann, & Henze, 2019). This result suggests that the proprioceptive system and coordinated control of hand and eye movement seem not to require all depth cues of one's own body. Such predictive modeling techniques can be used to inform design of XR applications such that they support human performance.

Another available engineering modeling approach is the Goals, Operators, Methods and Selection Rules (GOMS) model of human cognitive processing associated with human-system tasks (Card, Moran, & Newell, 1983). In this approach, each cognitive action is associated with a given processing time, and one can predictively assess the time required to conduct various interaction methods based on designs. The parameters and time estimates included in the original GOMS model were based on traditional desktop-based system interaction and may not be directly applicable within an XR environment. This, and other parametric models such as the Keystroke-Level Model, have yet to be extended to address XR interactions (Al-Megren, Khabti, & Al-Khalifa, 2018). Further research is required in this area to develop and validate engineering models for human interaction within XR spaces and systems. In particular, there is a need to extend the scope of such modeling approaches to tangible, physical, voice- and gesture-controlled XR interfaces (McIntee, 2016).

5.2 XR User Testing Methods

User testing involves representative users interacting with a system while their experience is measured in some way. Allowing users to interact with a system provides designers with (1) insights into how effective and efficient users can interact with the system, (2) the ability to identify unrecoverable errors that should be considered for redesign, and (3) the chance to gauge interest and user satisfaction from the experience. Interviews and focus groups provide a guided discussion on system design with users that provide qualitative data for designers. Formative studies evaluate users while interacting with a system, and look to quantify user interactions (e.g., speed, accuracy, errors), and provide hints to when users may fail to achieve desired performance. Summative studies are used to directly compare two or more systems/experiences using quantitative performance data of user interaction. Within formative and summative evaluations, there are many user testing methods available that may be utilized based on desired outcomes and resources available (Table 5). In a review of methods used in evaluating mobile AR environments, 69% relied on self-report questionnaires, while only 3% used performance metrics (28% used a combination

Table 4 XR Usability Principles

<table>
<tr><th>Nielsen's 10 heuristics</th><th>Additional VR heuristic considerations</th><th>Additional AR heuristic considerations</th></tr>
<tr><td rowspan="3">Visibility of system status—always keep user informed about what is going on</td><td colspan="2">Carefully design scenes with superimposed 3D objects and determine how camera should be pointed in XR scenes (de Almedia Pacheco, Guimarães, Correa, & Farinazzo Martins, 2018); Provide a frame designating input space (Ko et al., 2013)</td></tr>
<tr><td colspan="2">Minimize scanning and effort required to access information by maintaining information accessibility within display screen itself, or just outside its perimeter and accessible via a short head rotation at a body-referenced location (e.g., as if virtually mounted to a display attached to the wrist; Wickens, Dempsey, Pringle, Kazansky, & Hutka, 2018)</td></tr>
<tr><td colspan="2">Minimize frame-of-reference transformations, for example by superimposing a 3D AR grid directly onto the forward real world view (Wickens et al., 2018)</td></tr>
<tr><td rowspan="4">Match between system and real world—speak users' language, with words, phrases and concepts familiar to the user</td><td>User should always be aware of own location and spatial relations between self and virtual objects in the surround
Use visualizations and metaphors that have meaning within physical and task environment, which are presented to support natural engagement</td><td>Ensure virtual and real-world entities are combined in an elegant manner, with appropriate 3D registration and seamless real-time interaction when relevant
Real world should be basis of application—follow real-world conventions, and have information appear in natural and logical order
Size of objects should be appropriate to match real world; Switching attention between application and real world should be smooth
Adapt virtual content to environmental conditions (lighting/sound)</td></tr>
<tr><td colspan="2">Keep information sources that need to be compared (e.g., system map view and forward real world view) in close proximity (Wickens et al., 2018)</td></tr>
<tr><td colspan="2">Ensure persistence of positioning superimposed elements onto the real world regardless of camera motion speed (de Almedia Pacheco et al., 2018)</td></tr>
<tr><td colspan="2">Provide multimodal cues, such as spatialized sound and visual elements, when task-relevant information is provided (Ko et al., 2013)</td></tr>
<tr><td>User control and freedom—need clearly marked "exit" to leave unwanted state without having to go through extended dialogue</td><td colspan="2">Should be possible for users to choose between interaction methods—co-usage should be clear
Allow users to customize settings
Effect of user actions on virtual objects should be immediately visible and match expected behavior
Means of exiting virtual space should be explicitly communicated
Often controls are outside of the field-of-view in XR displays, and thus techniques to locate and orient to controls are necessary (de Almedia Pacheco et al., 2018)</td></tr>
<tr><td rowspan="2">Consistency and standards—follow platform conventions</td><td>Keep interaction simple and provide consistent responses to user actions</td><td>Manipulation should be natural—match characteristics of object and mental model of users</td></tr>
<tr><td colspan="2">Display elements in HWDs should be located, as much as possible, in the same relative locations with the same layout as in the real world (Wickens et al., 2018)</td></tr>
<tr><td>Error prevention</td><td>Design seamlessly and for disconnection
Ensure users can undo incorrect actions</td><td>Ensure system is useful and usable from a variety of viewing angles, distances and movements</td></tr>
<tr><td>Recognition rather than recall—instructions for using visible or easily retrievable cues whenever appropriate</td><td></td><td>Virtual objects should not occlude information that impacts usage of application</td></tr>
<tr><td>Flexibility and efficiency of use—experienced users provided shortcuts while novices are fully supported</td><td colspan="2">Allow users to skip non-playable and frequently repeated content; Minimize distraction and overload</td></tr>
</table>

(*continued overleaf*)

Table 4 (*continued*)

Nielsen's 10 heuristics	Additional VR heuristic considerations	Additional AR heuristic considerations
Aesthetic and minimalist design	Allow form to communicate function	Too many virtual objects should not be visible at one time to maximize legibility (Wickens et al., 2018) Provide intuitive and customizable input mappings Clearly separate virtual content from background in different usage situations (brightness/contrast)
Help users recognize, diagnose, and recover from errors	Design to avoid mistakes and prevent undesired actions Ensure system indicates problems precisely and makes suggestions in constructive manner	
Help and documentation—provide instructions, training and help	System should be intuitive and require minimal instructions and help *Position tracking:* Tracking must be fast and reliable to maintain position in real scene and minimize adverse effects; Consider accessibility of off screen objects *Presence:* Virtual representation of self (if present) should allow users to act and explore in a natural way; Users' perception of being in XR space should be natural *Physical comfort of use/ergonomics:* Device should not be too heavy, difficult to handle, cause physical load/discomfort, or limit normal physical actions; Device should not cause sickness or adverse aftereffects *System setup:* Keep environment setup (e.g., sensors/cameras, fiducial markers) as simple as possible *System safety:* Consider physical space constraints and appropriate design awareness cues for users; Ensure users are aware of own location and spatial relations between self and virtual objects in the surround	

Table 5 User Testing Methods and Metrics for XR Evaluation

Category	Method	Metrics
Explicit	Focus groups/ interviews	Guided discussion of system components/aspects and associated usability and user experience parameters
	Formative and summative evaluations	Self-report questionnaires: – System Usability Scale (SUS) – Post-study System Usability Questionnaire (PSSUQ) – Usability Metric for User Experience (UMUX) – Presence Questionnaire (PQ) – Workload Questionnaire (e.g., NASA TLX) – Sickness Questionnaire (e.g., SSQ) – Questionnaire for User Interaction Satisfaction (QUIS) – Smart Glasses User Satisfaction (SGUS) Questionnaire Overt performance (e.g., reaction time, accuracy/ errors) tracking and/or observation Think-aloud protocol—have users verbalize what they are doing and their thought process throughout interaction
Implicit	Formative and summative evaluations that use neurophysiological measures or 'unobservable' behavior	Eye tracking—visual search/attention Facial expressions via camera Linguistic analyses (e.g., voice intonation/ cadence/ amplitude, language used) Cardiovascular response (e.g., electrocardiography, respiration measures) Musculoskeletal response (e.g., electromyography, accelerometers) Neural activity (e.g., electroencephalography) Gastrointestinal response (e.g., electrogastrography) Stress response (e.g., electrodermal response)

of metrics) (Lim, Selamat, Alias, Krejcar, & Fujita, 2019). Obtaining user feedback early and often throughout design, development, and deployment of XR systems can enhance system effectiveness, while reducing cost and development time, which taken together can realize end results that better meet user expectations and needs. For example, Langlois, That, and Mermillod (2016) used user testing to systematically compare a real and augmented heads-up display on the basis of depth perception features. The user testing was able to benchmark AR designs to determine which ones ensured good congruence to real objects and thus would be expected to enhance SA and human performance.

Using self-report questionnaires during XR user testing provides a quick and easy method to gather user feedback. Questionnaires such as the *System Usability Scale* (SUS; Brooke, 1996, 2013), the *Post-System Usability Questionnaire* (PSSUQ; Lewis, 1992), and the *Usability Metric for User Experience* (UMUX; Finstad, 2010) are quick to administer and can be useful for uncovering problems, however, they cannot isolate what the problems actually are Other self-report questionnaires can provide insight into XR-relevant constructs, such as presence, how challenging a system interface/interaction may be and whether any adverse effects were experienced. Commonly used questionnaires include the *Presence Questionnaire* (PQ; Witmer & Singer, 1998), the *NASA Task Load Index* (Hart & Staveland, 1998) and the *Simulator Sickness Questionnaire* (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993). These have been used extensively to assess XR experiences and can provide useful data for assessing the impact of a system on user experience. Further, many satisfaction-based questionnaires have been developed—often tailored for a specific situation—that consider likability, pleasure, comfort, trust, flexibility in use, and safety of the user experience (Bevan, 2008). Measures of satisfaction, such as the *Questionnaire for User Interaction Satisfaction* (QUIS; Chin, Diehl, & Norman, 1988) and the *Smart Glasses User Satisfaction (SGUS) Questionnaire* (Xue, Sharma, & Wild, 2019), have been the most often used metrics for evaluating mobile AR solutions (Lim et al., 2019).

During formative (Chu, Chen, Hwang, & Chen, 2019) and summative (da Silva, Teixeira, Cavalcante, & Teichrieb, 2019) evaluations, a number of explicit and implicit metrics may be used to quantify an XR user experience. Explicit measures include task performance indicators, such as speed and accuracy. Users can be asked to talk aloud while interacting with an XR experience such that insights may be gained regarding their approach to interaction, frustrations, or points of confusion, as well as points of enjoyment, excitement, or enlightenment. This provides qualitative data to support quantitative data captured during an evaluation. In recent years, implicit measures have gained use in the usability community. Such measures provide insights into users' cognitive processing and interaction techniques using unobtrusive measures of visual attention, facial expressions, voice analysis, cardiovascular responses, musculoskeletal responses, and neural activity. These are particularly relevant to XR environments, which are designed to create immersive experiences where users feel and respond physiologically as a result. Having quantifiable data of such physiological responses can provide comparator data from which to benchmark XR experiences against their real-world counterparts.

6 APPLICATIONS

XR environments have been adopted by an ever-growing number of domains. VR, while initially used primarily in training and entertainment, has since expanded into diverse areas, such as system design and assembly. AR has seen rapid growth in recent years, gaining traction in enterprise training and support applications for maintenance, warehouse operations, as well as expanded entertainment offerings. These applications provide adaptable, deployable, and safety-conscious solutions at a modest cost, create game-based and learning virtual experiences that would otherwise be difficult to explore, and offer rehabilitation and medical applications that reach far beyond conventional computer-based options. The viral outbreak of COVID-19 in early 2020 and the associated lockdown drove adoption of XR (Mathur, 2020). XR technology began to be used to close the physical gap caused by social distancing, while connecting people in a variety of application domains (Papagiannis, 2020; Petrock, 2020; Redohl, 2020). XR has even been seen as key to maintaining military readiness during "Black Swan" events such as COVID-19 (Blades, 2020). This section outlines common and emerging applications of XR technology that will predictably surge over the coming years.

6.1 Training

XR technologies are being explored and/or deployed in a variety of training domains. Given the value of full-scale simulation-based training (e.g., full motion flight simulators, high fidelity medical manikins; see Chapter 16 by Bisbey et al. in this volume) that has been realized over the past few decades, the lower cost and mobility of AR and VR hardware platforms have allowed training developers to increase the return on training investment by providing a similar or better training experience for a lower overall cost (thedanse.com, 2015).

One area where XR technologies have gained a lot of traction in recent years is in maintenance training (see Figure 9). In an era where many professionals and amateurs alike are employing internet videos to learn or refresh their memory on how to diagnose and repair maintenance issues, AR provides an opportunity for maintainers to have videos, pictures, virtual models (or holograms) of equipment, and other types of media in their field-of-view while remaining hands-free to perform their work. Palmarini et al. (2018) found that AR is being used for aviation, automotive, train, plant, and general mechanical maintenance. Similarly, AR and VR technologies are being used in the construction industry for safety training and beyond, given that they provide an immersive experience without some of the challenges that can accompany on-the-job training, such as schedule conflicts, potential hazards, weather situations, and need for safety and liability (Li et al., 2017).

The medical domain is another area that is investing in using AR and VR for training (see Figure 9). Some examples of ways that VR is used include building virtual representations of organs and tissues to be viewed in depth in VR, learning to communicate more effectively with patients, providing training on how to diagnose and treat diseases, and surgical simulations (Hsieh & Lee, 2018). For example, surgical teams that are not co-located can train together by having the expert and trainee each wearing a HWD, such as the Microsoft HoloLens, and networked into the same scenario such that they are seeing the exact same visual representations. As the trainee simulates the surgical operation required by the scenario, the expert physician can provide feedback and guidance. Seymour et al. (2002) found that training residents in VR resulted in gallbladder dissections performed 29% faster than residents who did not receive training in VR. There were also significantly less errors made by the VR-trained group.

6.2 Education

Similar to training, the immersive nature, ability to provide visualizations in 3D space while keeping users safe, small form factors, and reduced cost are making XR technologies more and more popular as educational tools. Studies have shown

(a) (b)

Figure 9 XR training application examples: (a) maintenance; (b) medical.

that content learned via XR technologies can improve students' problem-solving skills, long-term memory, motivation, collaborative abilities (Alakärppä et al., 2017; Hung et al., 2017; Tobar-Muñoz et al., 2017), and learning performance (Pellas et al., 2017; Wei et al., 2015; Zhang et al., 2014). XR game-based learning experiences have been used to teach different Science, Technology, Engineering, and Mathematics (STEM) topics, such as natural, physical, and social sciences (Pellas et al., 2017). For example, a mobile AR application has been used to simulate molecule reactions for middle school student education (Ewais & De Troyer, 2019).

Teaching anatomy, physiology, and pathology of the human body is another great example (see Figure 10). There are a variety of AR and VR applications that render 3D stereoscopic visual effects to allow a user to visualize the different components and systems within the human body, often being able to add and take away layers of different systems to see how they interact with each other, allowing the user to zoom in on parts or rotate them, and allowing users to walk into virtual models to visualize what is happening inside (Hsieh & Lee, 2018).

Outside of the classroom, VR experiences are being developed to replicate real places, such as museums and monuments, to allow students to see and learn about history, art, etc. without having to travel to the actual places (Nikoletta et al., 2008). Similarly, an Honor Flight was filmed and implemented in VR allowing veterans in a hospice and not able to make the trip to experience it as though they had been able to travel (Walters, 2019).

6.3 Operations

While XR environments have been developed over the past half century, they have gained popularity as operational solutions in the last decade. In particular, XR enterprise based solutions are now being developed in key areas such as design, assembly, maintenance and repair, warehouse operations and remote expert access (Fink, 2019). As early as 1996, companies reported on their research into XR solutions for assembly tasks (c.f. Mizell, 1997). The automobile industry is using VR to design full-scale car models for design evaluation and test, allowing engineers, designers, and researchers from around the world to evaluate a design prior to prototype development (Schreiber, 2019). This application takes advantage of two key VR value drivers—reducing design time and increasing workforce collaboration (Deloitte, 2018). XR technologies are also being utilized in the design of spaces, such as

(a) (b)

Figure 10 XR education application examples: (a) anatomy, physiology, and pathology; (b) museum. *Source:* Adobe Stock/©ake1150 ©romaset. Reproduced with permission of Adobe Stock.

(a) (b)

Figure 11 XR Operational application examples: (a) architecture blueprints; (b) trucking operational support. *Source:* Adobe Stock/©zapp2photo. Reproduced with permission of Adobe Stock.

architecture, interior design, and plant design. For example, architects are able to use AR to create a 3D model of a building from blueprints (see Figure 11), share it with a large team of architects, plumbers, electricians, real estate investors, and construction workers so that all can quickly and easily test how equipment will fit and communicate design decisions (urdesign, 2017). Further, interior designers are able to test how elements, such as furniture, paint color, etc. will look and fit into a room, as well as share this vision with clients and architects using AR.

While VR solutions are providing benefits, it is expected that AR solutions will surpass VR utility within operational settings. By 2017, AR solutions were being tested in manufacturer assembly facilities and demonstrating performance improvements of 25–34% on first use (Abraham & Annunziata, 2017; Boeing, 2018; Capgemini Research Institute, 2018). Enterprise solutions for large-scale maintenance (e.g., aircraft, trucking industry; see Figure 11) benefit from the AR advantages of hands-free operation while accessing support documentation via digital, context- and spatially-relevant content within an HWD as opposed to paper manuals. This capability offers a more efficient and effective opportunity for maintaining equipment. In a similar light, inspections at construction sites are being supported by AR by having to-scale virtual models of building components superimposed on real buildings for a quick and easy visual indication of any differences (Li et al., 2017). Further, many systems are incorporating reach back capabilities to experts who can access a maintainer's view of a system and provide real-time support as needed to guide diagnostic and repair actions (Howard, 2019; Soldatos, 2019). Warehouse operations are benefiting from AR capabilities. For example, picklist processes showed a 46% gain in efficiency when using AR compared to standard process (Abraham & Annuziata, 2017). Utilizing HWD AR solutions allow workers to locate items and track movement without having to use handheld tracking systems, freeing hands to focus on picking and placing items. Mobile phone AR apps are also available, providing context-relevant content and reach back support for improved maintenance performance.

Surgeons are using AR to plan surgeries to increase the efficiency and effectiveness of surgeries and reduce the chance of errors (Hsieh & Lee, 2018). Pratt et al. (2018) used AR to overlay computed tomography angiography (CTA) images over a patient's body to demonstrate subsurface vascular anatomy before any incisions were made, aiding navigation and accurate dissection. Further, because AR headsets can be controlled through gestures and voice commands rather than touch, sterile conditions in operating rooms can be maintained.

For the general public, AR navigational solutions continue to expand and provide enhanced wayfinding and information discovery as one navigates their environment. Google Maps Live View was made broadly available in beta form in 2019, allowing users to see augmented directional cues overlaid on a mobile phone's camera view of the real world (Warren, 2019). The travel and tourism industry will continue to expand its use of AR apps, which allows travelers to navigate cities, identify and learn more information about landmarks and city sites, have up-to-date schedules and times of various transportation options and events, and translate foreign language signs for comprehension (Shah, 2019).

6.4 Entertainment

The entertainment industry has leveraged unique characteristics of XR experiences, providing dynamic and exciting exposures in a multitude of forms. XR entertainment applications have found their way into games, sports, movies, art, online communities, location-based entertainment, theme parks, and other venues (Badiqué et al., 2002; Burt, 2019; Nakatsu et al., 2005). XR technologies provide a more immersive medium for entertainment, as compared to more traditional entertainment media (e.g., film, play), through use of artificial virtual characters (i.e., avatars), engaging narrative, and dynamic interactive control to create engaging experiences.

VR gaming and entertainment accounted for US$4.15 billion in 2018 spending and is expected to grow to over US$70 billion by 2026 (Fortune Business Insights, 2019). Gaming accounts for about 50% of the VR software market, with adventure, action, and simulation games being most popular (Petrov, 2019). Actively engaging with online communities allows VR gamers to immerse into interactive worlds, seen from a first-person perspective. Often, game controllers are incorporated to support typical game-based interactions (pointing commands) and motion detectors are used to sense gamer's movements and replicate within the XR game. Interaction gloves are entering the entertainment market, which support more detailed hand movement control and potential for haptic feedback beyond "buzzing" indicators of contact (Ochanji, 2020; Zhu et al., 2020). With these enhanced, multimodal experiences, embodiment with XR characters is often more than that experienced with traditional PC/laptop games (Wilson & McGill, 2018; see Figure 12).

XR entertainment centers have gained popularity, where immersive experiences are provided as a service. DisneyQuest, which opened in 1998, was an early version of such a center, where users could experience VR (among other immersive experiences), such as riding a simulated roller coaster and navigating down rapids in a raft. Since then, more immersive, "location-based" VR experiences have been created where users enter and engage in an interactive world to achieve a mission

(a) (b)

Figure 12 XR entertainment application examples: (a) fully embodied VR; (b) Smartphone AR gaming apps. *Source:* (a) Shutterstock /©Kit8. Reproduced with permission of Shutterstock; (b) Adobe Stock/©Freer. Reproduced with permission of Adobe Stock.

(a) (b)

Figure 13 XR Sales and marketing applications: (a) virtual test drive; (b) in-store purchase support. *Source:* Adobe Stock/©ake1150 ©stockphoto-graf. Reproduced with permission of Adobe Stock.

(Rubin, 2019). Similarly, VR game arcades allow users to experience a broad spectrum of systems and games without having to purchase XR equipment (Castillo, 2018). In addition, popular roller coaster experiences have incorporated VR technology, such that riders can experience traveling through a virtual world while on the coaster (Michaels, 2016).

With the release of *Pokemon Go!* in 2016, AR games that overlay augmented content on to the real world surged in popularity (see Figure 12). This application provided a massive multiplayer online experience using smartphones that provided competition, collaboration, and familiar characters in an interactive experience, tracking user location relative to virtual elements placed around the globe. Since that time, a number of AR games have been released and popularized in various user communities (Long, 2019). With this enhanced, connected entertainment opportunity comes risks, primarily focused on security and safety (Banister & Hertel, 2018). The industry must carefully consider and account for potential issues in these areas to continue to see sustained growth and utility.

Simplistic, widely available AR experiences have emerged with smartphone technology, particularly via facial filters or lenses. In 2015, Snapchat was one of the first applications allowing users to add AR content to images/videos that were captured on their phone. This capability utilized facial recognition technology to pinpoint users within a scene and offer various AR characteristic add-ons. Filters have become widespread and are now available in various applications, such as Instagram, Boo!, SNOW, Camera360, and Face Swap Live (Moreau, 2019), to personalize characters and share photos/videos with friends. With the plethora of self-altering filters, there are concerns regarding self-image and self-esteem, particularly in teenage girls (Ehmke, 2020). Rauschnabel (2018) developed a theoretical model of gratification expectations from AR enhancements to the real world. Further research to better understand the societal impact of such enhancements, which are becoming the “new normal” in self-imaging, is needed to optimize this available technology to support human growth and entertainment while minimizing negative impacts related to mental health concerns (Kenwright, 2018).

6.5 Sales and Marketing

Companies are also beginning to discover the value of transitioning from common video-based marketing experiences to fully immersive XR experiences. In fact, 75% of Forbes World’s Most Valuable Brands have developed some form of XR experiences for customers or employees (Korolov, 2015). Brands such as Lowe’s, IKEA, BMW, Audi, and Porsche have integrated XR experiences into their marketing strategy. Examples of VR use for marketing include a VR tour of an airline business cabin, a 360-degree panoramic view of a fashion runway show during London Fashion Week, a VR experience to test drive cars, and

Figure 14 Immersive realtor applications. *Source:* Adobe Stock/©ArchiVIZ ©sharplaninac. Reproduced with permission of Adobe Stock.

supporting in-store furniture purchases by examining different material swatches (mbryonic, 2019; see Figure 13).

Realtors are also using VR to allow potential buyers to experience a “virtual walk-through” of a house or building in first person that can be viewed either on a mobile device such as a smartphone or tablet, or in a VR headset. They accomplish this by taking a series of pictures with a 360^0 camera that are then integrated to provide an immersive experience. Realtors are using AR to promote home and business sales by incorporating virtual models of furniture into real rooms, allowing potential buyers to visualize how furniture can fit into their space without the added cost and time required for staging (urdesign, 2017; see Figure 14).

In general, AR techniques are becoming popular with in pre-purchase sales situations (e.g., fashion “try-ons,” International Data Corp, 2017; retail showcasing such as decorating spaces, Dacko, 2016) and eCommerce in general (e.g., previewing product modifications, exploring features), as they have been demonstrated to vastly increase sales conversion rates (Saleem, 2019). These benefits of AR sales and marketing are thought to derive from a heightened sense of ownership when engaged with digital products, immersive storytelling, wonder, and social status associated with crowd-sourced product reviews.

7 CONCLUSION

eXtended Reality represents the next stage in the evolution of a capability rooted in an early twentieth-century requirement for safely training individuals to master a challenging skill set—manned flight (Chihyung, 2015). Yet, in one sense, the concept of simulating reality dates back thousands of years, to the ancient Egyptians, who used physical models to simulate war planning, and the ancient Chinese, who built elaborate “automata” to train soldiers in combat (Amico, 2009). While it would be a stretch to say that these earliest efforts directly trace to today’s capabilities, it is accurate to suggest that the primary challenge faced by XR—developing solutions that effectively mimic reality—is similar to that encountered by those early efforts. What have advanced over time are the approaches available to creating these solutions. This chapter has provided an overview of these advances, from the technology, design, and application perspectives.

From a technical perspective, advances in the underlying hardware, ranging from headsets, to tracking, to interaction, have made XR solutions less expensive, more powerful—hence of higher immersive quality—and more accessible to a broader range of users. Paralleling these hardware advances, software advances have made design of environments rendered in XR, and development of the content that populates those environments, more sophisticated, further increasing the immersive quality of these systems.

From a design perspective, XR poses unique challenges. The user population drives design considerations, making a “one-size-fits-all” approach impractical, requiring consideration of a range of factors that include: identifying the best manner in which to convey specific types of information; determining the best approaches for allowing users to control the flow of the XR experience; and, specifying the level of interactive fidelity necessary for an effective immersive experience that minimizes cybersickness. These user design considerations are best considered in terms of a tradespace driven by technology considerations. Critical boundaries on solutions deriving from this tradespace analysis, which should be considered when developing XR applications, include ensuring the health and safety of all users as well as the social consequences of making these systems available. Designed correctly, user testing can provide deep insight into these and other critical boundaries.

The applications for XR continue to evolve as the underlying technologies and designs advance. As recently as a decade ago, the cost of the infrastructure required to design, develop, and maintain these systems was a critical barrier to entry for many users. Today, these core technologies can be had relatively inexpensively. As a result, XR is now more accessible for education and training, collaborating and partnering, networking and entertaining and more uses than ever before. Advances in networking infrastructure, increased access to the internet through wireless technologies and the advent of cloud computing and storage continue to democratize XR, ensuring that new uses and applications will continue to emerge far into the future.

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