Immersive Technology and Medical Visualisation: A Users Guide

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Abstract The immersive technologies of Virtual and Augmented Reality offer a new medium for visualisation. Where previous technologies allowed us only two-dimensional representations, constrained by a surface or a screen, these new immersive technologies will soon allow us to experience three dimensional environments that can occupy our entire field of view. This is a technological breakthrough for any field that requires visualisation, and in this chapter I explore the implications for medical visualisation in the near-to-medium future.

First, I introduce Virtual Reality and Augmented Reality respectively, and identify the essential characteristics, and current state-of-the-art, for each. I will then survey some prominent applications already in-use within the medical field, and suggest potential use cases that remain under-explored. Finally, I will offer practical advice for those seeking to exploit these new tools.

Keywords: Medical Visualisation; Virtual; Augmented; Reality; Immersive;

1. Immersive Technology

Anatomical structures and physiological processes occur in three dimensions, and much of what takes place within the human body remains beyond our natural perceptual faculties – either too small too see, or obscured under the skin. Whilst the techniques used to capture these structures or processes for visualisation advanced dramatically throughout the twentieth century – from radiography, to (functional) magnetic resonance imaging – the means by which we actually viewed the captured data remained confined to two dimensions, and to the surface of a sheet or screen.

We have been exploring three-dimensional (3D) structures, via two-dimensional (2D) media.

The advent of immersive technology offers a breakthrough for this historic mis-match between the information we want and the representational mode that we have available. The term ‘immersive technology’ actually covers two different technologies that allow engagement with 3D information in a 3D medium: Virtual Reality (VR), and Augmented Reality (AR). Whilst these technologies differ in their features, they share a common technological core in the ability to render 3D computer environments in such a way as to allow the user to perceive virtual objects in much the same way as they do objects in the natural world.

In this chapter I will introduce these technologies, comment on their current, and hypothesised, application within medical visualisation, and offer practical advice on how practitioners should go about integrating immersive technology into their work. In sections 2 and 3, I will lay the groundwork for understanding what is possible, and discuss the essential features of VR and AR respectively. I will give a snapshot of the current state-of-the-art hardware, as well as some predictions about progress in the medium term. In section 4 I will discuss existing applications for training, diagnosis, and treatment, before outlining some future applications that will be viable once the hardware has further matured. In section 5, I will offer practical advice about what makes for a good application of immersive technology, and what does not.

2. Virtual Reality

The term ‘Virtual Reality’ appears to have been coined by Jaron Lanier, a pioneer in the field, in the 1980s (Lanier, 2017). Lanier launched a VR software and hardware company (VPL) in 1984, and went on to popularise the technology over the following decade. It is clear that his work paved the way for the systems we have now, however Lanier points to the work of Morton Heilig[1], and Ivan Sutherland[2] in the 1950s and 1960s as having made the crucial early technological breakthroughs.

After its initial rise to prominence in the late 1980s and early 1990s, VR soon faded in popularity in part due to the cost of the hardware, and in part due to the poor user experience on offer – VR nausea was commonplace. Whilst VR continued to be used in industry and research niches, it took the announcement of the Oculus VR system on *Kickstarter* in 2012 for the current VR renaissance to take hold. Oculus was purchased by Facebook for $2 billion in 2014, and launched the Rift in 2016. HTC teamed up with Valve (the makers of gaming platform *Steam*) to launch the Vive VR system less than a month later, in April, 2016. As of 2018, there are dozens of headsets available to consumers, and within the next decade, it is widely expected that immersive headsets will become ubiquitous.

2.1 Virtual Sight, Sound, and Touch

Virtual Reality technology intervenes on the senses to represent a virtual environment in place of the real one. Current hardware achieves this through a headset, worn by a user, which presents slightly different images to each eye via a combination of high-resolution screens, and carefully constructed lenses. The software element of the system is able to take information about the head position, and movement, and dynamically render an accurate perspective of the virtual world to the user. So, when a user looks up, or down, or even behind them, the scene that is delivered to each eye is as it would be if that environment were being naturally perceived. The result is that, to varying degrees, the user feels *immersed* or *present* in the virtual world (Champel, et al., 2017).

This characterisation privileges the visual dimension to VR, but most systems also use the same software calculations about head position to mimic directional audio. Thus, not only are the visual cues consistent with the presence of the virtual objects, the audio cues are too. There is evidence to suggest that the combination of visual

[1] http://www.mortonheilig.com/InventorVR.html

[2] https://en.wikipedia.org/wiki/Ivan_Sutherland

and auditory input for a VR experience significantly magnifies the sense of presence for users (Brinkman, et al., 2015).

What remains most clearly missing, at least for the time being, is a highly realistic haptic dimension to virtual experiences. What do exist are prototype gloves, suits, and robotic arms that mimic genuine haptic engagement to some degree (Pacchierotti, et al., 2017) but the resistance and weight that we feel when, say, lifting a bowling ball, or baseball bat, remains beyond the reach of all but the most specialist, and custom-built, solutions (i.e. by placing a VR tracker on a real-world bat). Among the openly available VR systems, haptic effects today are largely limited to mild rumble effects in hand-held controllers. This is particularly relevant for the medical field, and I will return to this issue in section 4.4.

2.2 Virtual Movement

Another significant dimension to immersion, is the issue of movement within VR . Movement mechanisms vary between hardware systems, and even between software applications, but they split into four broad categories:

- Static: the user is rooted to a single position in three-dimensional space, but can still look around by tilting their head along each of the X, Y, and Z axes. This gives the user only three degrees of freedom (3DoF) in the virtual environment.

- Continuous motion: using a gamepad, or controller, users can instruct the camera or avatar in VR to continuously advance through virtual space along the X, Y and Z axes. This allows virtual locomotion, and so up to six degrees of virtual movement (6DoF), even if the hardware can only track 3DoF user movement in the real world.

- Teleportation: like continuous motion, this uses a gamepad or controller to move, and allows 6DoF virtual movement, even on 3DoF hardware. However, unlike continuous motion, this method of movement takes the user abruptly from one point in virtual space to another.

- Tracking: more advanced "room-scale" VR systems[3] can track the user's real-world movement in all six dimensions (tilting *and* movement through X, Y, and Z). Using this method, virtual movement can match real world movement.

The simplest of these to execute is the static approach, but it is also the least rewarding in terms of presence or immersion. If you take a step to the left, or crouch, in the real world, but the virtual perspective remains unchanged, that breaks the sense that you are really *in* that virtual environment (Champel, et al., 2017).

By contrast, the most complex, and most satisfying, approach is that of tracking. When every move you make is matched in the virtual world, then immersion and presence are at their peak. This approach requires real world space, however, and your movement in the virtual world is limited to where and how you can move in the real world. For this reason, it is standard to blend the tracking approach with one of the controller-based strategies.

Of the controller-based approaches to movement, teleportation may seem like the most unnatural – we cannot teleport in the real world, but we can walk or ride as we do with the continuous movement approach. It turns out, however, that continuous movement is a significant contributor to virtual reality nausea as it creates a mismatch between the visual information provided by the VR system, and the real-world inputs detected by the vestibular system (Akiduki, 2003). Thus, teleportation has become a standard way for users to move in VR.

2.3 VR Hardware

VR Hardware comes in three broad categories:

- Phone-in-a-box
- Standalone
- Tethered

The phone-in-a-box variety was the first to become widely available in 2014, (Lunden, 2016). It combined a box-frame and lenses with the existing high-resolution

[3] Current examples include the HTC Vive, Oculus Rift, and Samsung Odyssey.

screens, and gyroscopes, in modern smartphones, to create a simple VR experience. The earliest versions such as the Google Cardboard, and the Samsung Gear, allowed anyone with a sophisticated enough phone to experience VR very cheaply (from around $10). These experiences were limited, however, by the resolution, graphical power, and battery of the phone, and – since separate controllers were not available initially – by the strict limitation of having only 3DoF movement within the virtual experiences.

In March 2016 Oculus launched their much-anticipated *Rift*: a *VR* system that had to be *tethered* to a PC for power and graphical processing (Lomas, 2016). The Oculus allowed 6DoF movement in the real world to be tracked by two sensors (also tethered). Just a few weeks later in April 2016, HTC launched their tethered system, the *Vive* (Vive, 2016). This system did not require tethered sensors, but rather infra-red beacons by which the headset could triangulate its own location. This allowed for even greater freedom than the standard two-sensor Oculus system, and was arguably the first truly *room-scale* VR system available to the public.

The *standalone* systems – such as the Oculus Go, and the Vive Focus – are dedicated VR systems, so do not use a further device such as a phone or a PC. This means that they are independent of sensors, beacons, or a PC, unlike the *tethered* sort. The Vive Focus offers 6DoF by using an *inside-out* tracking system that senses the environment and uses that to triangulate head motion (Vive, 2018).

The additional processing resources of the *tethered* systems allowed for considerably more ambitious graphics, but more importantly it enabled a very high image refresh-rate (90Hz) that appears to have significantly reduced VR nausea issues (Hunt, 2016). Without the power of a PC, the *phone-in-a-box*, and *standalone* headsets available as of 2018 offer a compromise in terms of refresh rate (60Hz – 75Hz) and graphical quality. However, without the bulk and expense of a PC, they offer more portable, and more affordable option.

The ideal VR Hardware system remains elusive, but significant progress can be expected in the short - medium term (1 - 5 years) towards a more ideal system that is standalone, affordable, and which has the kind of processing power currently reserved for tethered systems.[4]

2.4 VR Feature Set

As the foregoing should make clear, there is much diversity within the current VR hardware offering, so there is no definitive "VR feature set" that would fit all cases. That said, if we set aside the *phone-in-a-box*, and more limited *standalone* headsets, we do get significant convergence on the following.

VR experiences involve computer generated environments. Even when the content is a 360-degree movie, or an environment built from photographs, what is being experienced by the user in the moment, is computer generated. Just as with CGI techniques in films, this removes the constraints of the actual world. You can experience distant or unreachable places, journey to the past or the future, occupy molecular or galactic scales. You can forgo gravity, manipulate light and sound, you can destroy mountains, or produce objects *ex nihilo*, or adopt super-human perceptual abilities. In short: anything goes.

VR experiences offer a realistic sense of virtual depth and 3D. When in VR, you experience the environment as being genuinely three dimensional, and you can assess depth (and so height, and scale) in a natural way. In application, this means that users can be shown an object or environment in VR and genuinely grasp its 3D structure without the interpretive work required when only presented with 2D media.[5]

VR is Immersive. Perhaps the primary driver behind VR technology is its ability to make the use feel as though they are genuinely present in the virtual space. This can be used for games, or leisure in obvious ways, but it can also help with training and education in much the same way as real-world field trips, or practical observations, do.

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[4] In October 2018, Oculus announced the Quest standalone system, which will be launched in Spring 2019 (Oculus, 2018). The explicit claim is that this will have "Rift-level" visual quality, but at the time of writing, this quality claim remains unverified.

[5] Though depth perception appears to err systematically in VR (Thompson, et al., 2004).

VR is isolating. Since VR intervenes on the senses to represent a virtual environment, it screens-off the actual world, and the people who are in it. This isolates the user – a bonus for immersive gaming, or meditation, but perhaps a demerit for certain teaching or social applications. This is the flip-side of immersion – it is the price we pay for feeling like we are in the virtual world.

VR can be disorienting. Coming out of VR, many users take a moment to re-adjust to the real-world surroundings. The lighting is different, the colours less vivid, and their orientation within the room may be surprising. This can all be mildly disorienting, but after having given hundreds of VR demonstrations, I have never experienced that disorientation become distress. That said, the potential for more severe reactions is there, and practitioners need to bear this in mind, especially when dealing with vulnerable populations.

~~*VR is nausea-inducing*~~*.* VR certainly *was* nausea inducing in the past, but the high refresh rate issue has eliminated this as a *general* VR feature. I cross it out, but do not delete it, because nausea does remain an issue if developers are not careful with their approach to virtual movement. It has become a matter of choice, not an essential feature of the technology.

I will return to this list in section 5 when I offer my practical advice. I now turn to the sister technology of Augmented Reality.

3. Augmented Reality

Augmented reality technology intervenes on the senses to create a realistic impression of virtual objects within the real environment. Where VR aims to replace the real-world environment with a virtual one, AR aims to integrate virtual elements with our real-world surroundings. It is tempting to think of AR as a kind of partial VR – if VR aims to take over 100% of the experience, AR aims for something less – but this characterisation risks giving the misleading impression that AR is easier to achieve. Achieving fully-functional AR is considerably more complex, and technologically challenging, than VR (Ashley, 2015).

3.1 AR, MR, and HUDs

What exactly deserves the name 'augmented reality' has been somewhat controversial. At launch in 2011, Google Glass was heralded as a breakthrough 'augmented reality' device available to consumers, and yet many would argue that Google Glass merely puts a small screen between you and the world. Such screens have been around in the military and elsewhere for a very long time, and are typically referred to as Heads-Up Displays (HUDs) (Wikipedia contributors, 2018). The characterisation I give above rules out Google Glass (and others, such as the Vuzix blade (Statt, 2018)) as AR, since there is no integration of the contents of the screen into the real environment, there is merely a display between you and the world. So, in my parlance at least, HUDs are not AR.

Another rival term that is sometimes used is Mixed Reality, or MR. This nomenclature seems to have arisen in an attempt to distinguish technology that integrates (*mixes*) with the real world, form that which merely overlays upon it (as with HUDs). Again, on the characterisation of AR given above, no additional terminology is required in order to make this distinction, so I consider this unnecessary, but it has mainly gained currency through a concerted effort by Microsoft to create a unified brand around their efforts around VR and AR. I will stick with the more neutral terminology of AR.

3.2 AR Hardware

The primary challenge of AR is to make the virtual *fit* with the real, in a convincing or helpful way. This is what makes perfecting AR more difficult than VR, since VR can largely ignore the real-world environment entirely, but AR systems must in some sense detect the world.

There are three main technological approaches to this:

- *Trackers*: use distinctive, high-contrast, images or patterns in the real world (e.g. QR codes) to give the AR device a point of reference by which to orientate and locate the virtual object in the scene.

- *Basic SLAM*: Simultaneous Localization and Mapping (SLAM) is the process of having a device *map* an unknown environment, and *locate* itself within that environment, in real time. Basic SLAM, as I refer to it, predominantly uses the optical inputs from a camera, together with a gyroscope and/or accelerometer, to achieve this understanding of the environment, and to approximate its location within it.

- *Advanced SLAM*: This uses an array of sensors, including stereoscopic cameras, infra-red sensors, gyroscopes, and accelerometers, to accurately map the environment, and position the device.

The first AR systems to be widely available, were those which used smart-phone, or tablet, cameras to detect the size and orientation of *trackers* in the environment, and then render virtual assets (3D models, virtual video screens, etc.) relative to those trackers. The result played on the phone/tablet's screen integrated with the standard camera's feed. This can yield impressive results, especially when users control the size and orientation of the virtual objects by varying the distance and orientation of the tracker (Azuma, 1997).

The tracker approach is quite seriously limited, however. Firstly, the rendering of the virtual object is insensitive to what else is in the environment, so rendering large objects in small spaces, or objects which should be partially obscured from your perspective, ends up looking like a poorly-executed photoshop edit rather than virtual objects integrated into the scene. Secondly, this approach requires that we alter the real world in some way (i.e. printing QR codes) to trigger the AR experience. This makes scaling the experiences difficult, and severely limits the range of use cases to which AR can be applied.

SLAM technologies require no pre-set aspect of the real-world to latch-onto. Their major strength is that they can operate in a wide variety of *unknown* environments. This places greater strain on the device, however, both in terms of processing load, and in terms of sensing ability, so whilst trackers could work on older camera phones (Samsung Galaxy S6 era), even *Basic SLAM* requires newer, more sophisticated devices (iPhone 7 era onwards).

Much can be done with even *Basic SLAM*, however, as the success of Pokémon Go showed in 2017 (Chamary, 2018). By detecting real-world surfaces such as floors and tables, devices are able to render virtual objects – like Pikachu – into the scene quite realistically. Both Android and iOS platforms now include a native AR capacity using this sort of SLAM technology, and developing and publishing for AR has become vastly easier as a result.

Advanced SLAM remains the obvious next step. With an array of sensors, devices can detect more than just basic surfaces. They could, (in theory) detect the size and shape of objects, and their depth from the device. This would allow for realistic placement, even in cluttered or busy scenes, and (eventually) realistic occlusion by intermediary objects. As of 2018, there are only two broadly-available devices that are capable of this kind of Advanced SLAM AR: Microsoft's HoloLens, and the Magic Leap One.

The HoloLens was launched as a "Mixed Reality" prototype spectacularly early, in 2016, and remains largely unchanged (and still restricted to developers only), in 2018 (Microsoft, 2018). The HoloLens is not a phone, but a wearable headset, with transparent lenses that sit in front of the eyes, like a visor. Both the HoloLens, and Magic Leap's One, use novel projection techniques instead of a screen. The benefit of this is that virtual objects can be represented as occupying a part of the visual field, whilst the rest remains naturally perceived by the user. This is a major advancement over the pass-through approach on smartphones and tablets, where the entire scene, including the real-world environment, had to be viewed via a screen.

As extraordinary as the head-mounted, Advanced SLAM, devices are, they remain impractical in two main ways. First, they are prohibitively expensive, at $2,500 - $3,000 each, and neither will be available to the general public until mid-2019 at the earliest – perhaps never, in the case of the original HoloLens. Second, they can only render virtual objects in a narrow portion of the visual field: around 30 - 40 degrees compared to the 90 degrees we get on VR headsets like the Vive (Ashley, 2018). The effect of this is that when a user looks off to one side, the virtual object either clips, or disappears entirely, from the scene. It can seem like you are looking down a tube at the world.

In the medium term, however, we can expect the projection technology to improve, the cost to come down, and the bulky/awkward form factor to be refined. There is good reason to think that AR headsets in 2030 will have replaced the smartphone, as we will no longer need a screen to see our data – it will be overlaid on the world around us in a whole new data interface.

3.3 AR Feature Set

It is useful to consider the feature set associated with AR, by contrast with the feature list for VR.

AR uses computer generated elements in real environment: As with VR, every virtual element is computer generated and so not bound by the rules of the real world. You can have a virtual screens at your desk, distant people virtually in the room with you, or virtual arrows directing your actions. Almost anything goes.

Integrated with real world: Whilst VR ignores the real world, AR enhances it. You can have any available sort of information – temperature, blood pressure, scans, etc. – appear on the organ, or patient in front of you.

AR is partly-Immersive: VR takes you away from the real world, and immerses you in the virtual. AR leaves you in the real world but can, to a lesser extent, immerse you in as different version of the real world.

AR can be a shared experience (non-isolating): Since AR leaves you in the real world, it leaves you in touch with the objects, and people, in your actual environment. This makes group tasks, or collaborations, around some virtual object much more natural and effortless than in VR.

AR can be orienting: AR does not disorientate users in the manner that VR can, as it leaves them in an enhanced version of the world – potentially one with in-built directions.

AR does not cause nausea: As there is no mismatch between perceived movement and actual movement in AR, nausea is simply not an issue.

4. Immersive Technology in Medical Contexts

With the groundwork laid in terms of VR and AR hardware and feature sets, I will now outline three use cases where immersive technology has already been applied in the medical sphere. One is in the context of medical training, one in diagnosis and pre-surgical planning, and the last is therapeutic.

4.1 Immersive Technology and Medical Training

Perhaps the most common application of immersive technology to the medical sphere, is in training and simulation. Using realistic (though generic) 3D computer models, applications using VR and AR can help impart genuine 3D understanding of the anatomical structures, and physiological processes, within the human body.

One prominent example of this, is the Medical Realities Platform, which takes users through several stages of surgical training, appropriate for undergraduate or postgraduate level (Medical Realities, 2018). Specific lessons on the app include various different laparoscopy procedures, and a series of 360 degree videos within live surgeries, which allow the student to experience the realistic context. This application is published across all VR platforms for broad reach, but in order to remain accessible to those on the likes of Google Cardboard, the app functionality is limited to 3DoF experiences, with basic, or no, controller interaction.

At Case Western University, the School of Medicine partnered with Microsoft to trial the use of HoloLens in teaching anatomy (Case Western University, 2015). Using AR, rather than VR, allowed a natural interaction between students and teachers – gesturing at particular elements when explaining, or asking about aspects of the animation. Students could view the brain, heart, or digestive system from any angle, and can strip away layers of the model to see the underlying structure, or function.

The practical limitations of the HoloLens prevent widespread adoption of this approach today, but it is clear that the students and staff felt the move to 3D teaching was transformative:

"students who had used the HoloLens devices reported that 15 minutes with the three-dimensional images "could have saved them dozens of hours" in their traditional anatomy labs" – Dean Pamela Davis, School of Medicine (Case Western University, 2015).

4.2 VR, Diagnosis, and Surgical Planning

If volumetric information is available for a patient, then volumetric rendering, and viewing, of that data could allow greater insight in diagnosing a condition, or planning a surgery. That is the motivating thought behind the "Anatomy Viewer" application, from Body VR (The Body VR, n.d.).

This application takes patient-specific medical data from MRI, CT and PET imaging, and allows users to view that data in 3D through VR. Instead of having an array of 2D slices of the brain represented in individual scans, practitioners can instead see the combined structure in 3D, and interrogate the information without the cognitive effort of translating 2D information into 3D understanding. There is some evidence to suggest that this can speed the process of surgical planning, and increase accuracy (Stanford University, 2017), but it should also be able to help patients understand their condition.

In the future, this sort of application could be extended to take advantage of better AR hardware, so that the 3D models can be seen by doctors and patients simultaneously, or can be available as a reference during surgery.

4.3 Therapeutic Applications of Immersive Technology

Where training and diagnostic applications predominantly have the medical professional as the user, the therapeutic applications have the patient engage in the immersive experience. I will highlight three existing applications of this technology: in stroke rehabilitation, in the treatment of phobias, and as a non-pharmaceutical analgesic.

Stroke: Motor recovery is a major element in post-stroke rehabilitation, and there have been dozens of trials of using VR to aid with this. A meta-analysis of those trials conducted showed that the approach had promise (Saposnik, et al., 2011). In early 2018, the Magic Moovr app was launched with the explicit aim of aiding motor recovery in stroke patients, by having them play an immersive game in VR. It is worth noting that this sort of approach will always require VR systems that can either track the movement of the body, or controllers, in 6DoF, and so wide adoption may be stymied by the availability of the hardware.

Therapy: Exposure therapy is a widely used treatment for phobias, and for PTSD, but it requires repeated, incremental exposures to the target of the phobia – spiders, heights, triggering environments etc. VR offers the opportunity to iterate those incremental exposures safely, cheaply, and with greater frequency. A recent literature review of clinical applications concluded that VR-based exposure therapy “has demonstrated equivalent outcomes to *in vivo* exposure, the gold-standard treatment" (Maples-Keller, et al., 2017). Whilst promising, the review also notes that existing studies have had low numbers of participants (10 – 20), and typically no control group.

Analgesic: VR has been used as a non-pharmocological analgesic in the amelioration of both acute and chronic pain (Hoffman, et al., 2011). It has been hypothesised this works by diverting the patient's attention to the virtual world, and thereby leaving less cognitive capacity for the processing of pain signals (*ibid*.).

4.4 Future Directions

In the future, I expect that we will see considerably more use of VR and AR in the training, diagnostic, and therapeutic applications outlined above, but the major revolutions in the application of immersive technology to medical visualisation awaits two key hardware advances: realistic haptics, and remote presence.

Realistic haptic feedback is essential to realistic simulation of tactile tasks, and it remains the most serious technical barrier to the meaningful displacement of cadavers in surgical training. Without realistic *feel* and super-precise (sub 0.1mm) tracking, VR will not be able to sufficiently simulate the target circumstances to allow surgeons to develop the necessary motor skills.

Several solutions have come to market to try and address the haptic issue, including Xitact medical simulators, and 3D System's *Touch* device[6]. A systematic review of the available technologies in 2016 concluded:

> "While haptic simulations are an interesting and low cost alternative to training by using real tissues, they are still hindered by the low realism of the visual environment or the high price for high quality devices." (Escobar-Castillejos, et al., 2016)

This is likely to remain the case for some time yet. The present devices focus on providing realistic *resistance* to the user, so that there is some physical sensation of presence to the user, even when there is no real-world object in front of them, and this is achieved by having the user handle a proxy object (the haptic device) instead.

[6] https://uk.3dsystems.com/haptics-devices/touch

However successful such devices are in that dimension, they lack the additional qualities of touch such as texture, and temperature, as well as limiting the mode by which the user feels them – you cannot detect pressure on the back of the hand or finder, for example. These combined challenges remain substantial, but it is clear that the medical industry is leading the way.

Remote presence is another avenue of significant potential, but it represents an equally significant technical challenge. The idea of remote presence is that the user of an AR or VR system could experience the virtual presence of a remotely-located person, as though they were in fact in the room. This means that they can see, and be seen by, those in the room, together with the physical surroundings, and communicate naturally with the expressive power of gesture, and the nuance of facial expressions and body language.

One major benefit of such a technology would be that a world-expert in some procedure or topic could be virtually present in seconds, if required, and present in a second surgery moments after leaving the first, regardless of geography. Once we see the potential in that case, it is becomes obvious that the benefits really apply far more broadly, perhaps to include the virtual presence of a doctor with a paramedic crew, or with a patient.

This technology will require not only the highly-accurate mapping of the target environment (i.e. the operating room), from all angles simultaneously, it would also require a highly-accurate capture of the remote person, such that their expressions, their movements and gestures, could be conveyed to those physically present, whilst they in turn see the target environment via some face-covering device. These are substantial enough technical challenges on their own, but for remote presence to function well, it will require that both are solved, *and* that the two-way communication of the captured information is fast and reliable enough to make the presence work in high-accuracy, high-stakes, applications (compare with voice delay on long distance calls).

5. Practical Advice

A future with realistic haptics, and remote presence, in medicine could be bright, but for the time being applications need to be designed within the practical constraints we face today. In this final section, I outline some practical advice for those seeking to develop applications using immersive technology.

5.1 Do

Do consider your target audience, and their practical limitations. If you are aiming to reach the masses, then niche devices like the HoloLens, or even the HTC Vive, are simply not established in a wide enough population to be the appropriate platform. If you are targeting a highly specialised audience, consider whether the environment they will use it in can incorporate the sensors or beacons that may be required for room-scale VR.

Do consider the limitations of the platform you are targeting. For applications with significant movement for the user, avoid the 3DoF systems, and the nausea-inducing continuous movement approach to virtual locomotion.

Do try and match the application to the feature set of each technology. VR should be used for immersive, isolating, experiences where the user gets the sense that they really *went* somewhere, or genuinely *did* some task. AR should be used when it is an *object* that needs to be scrutinised, or manipulated, rather than a whole environment, or when it is important that you remain oriented in the real-world environment.

Do use the superpowers that immersive technology allows.[7] Unaided, we cannot see light of certain frequencies, we cannot see temperature, or colourless gasses, or *inside* opaque objects, or what they looked like in the past, or should look like after a procedure. Given the computer-generated nature of the virtual, these limitations simply need not apply in AR and VR applications. Thinking of what we would *want* to be able to see, or hear, or feel in a context is the first step to really exploiting this new media.

Do start planning today. The hardware may not be ready for your desired application today, but designing and planning the application in advance, and prototyping it on non-ideal hardware, will give an extremely valuable head-start when it is ready. For example, apps that will require sophisticated AR hardware, can be prototyped very

[7] It is interesting to note that Iron Man has no *inherent* superpowers, but his use of technology – including AR – puts him on a par with those, like Captain America, or Thor, who do.

effectively in top VR systems today. The connection with the real world will need to be faked at first, but the learning and development that take place in VR should port easily to AR once the hardware matures sufficiently.

5.2 Don't

Don't use immersive tech for the sake of it. If the application you want could be done via videos, interactive web-apps, or using some cheap physical props, then immersive technology represents an expensive, restrictive, and over-engineered solution to the problem.

Don't model what you don't have to. The smooth running, and visual quality, of an app significantly depends upon how well *optimised*, the virtual environment is. Given the extraordinary processing requirements of AR and VR, and the bottleneck that processing represents for many devices, processing unnecessary detail in the virtual scene can seriously impact on the quality of the experience. Simplified backdrops in VR, or textures in AR, will typically improve the performance without sacrificing the experience. Note that one bonus of AR apps is that you get the real-world environment for free (both in terms of cost to develop, and processing load).

Don't overstimulate the user. VR in particular can become overwhelming for users if too much is going on, and too little time is allowed for them to look around, and find things in the virtual environment at their own pace. A common problem in the design of AR and VR applications, is that users do not naturally know where they are supposed to direct their attention. This issue is compounded by overly complex experiences.

Don't incorporate unnecessary movement. Given the technical challenges around movement, and the potential for nausea and disorientation, it is wise to limit the movement within the experience as much as is practically possible. One counterpoint to this is the additional immersion VR users can experience if they move, even just a little, to experience the 6DoF tracking.

Don't overlook the haptics. It should be plain from the above discussion that only fairly basic haptic feedback technology exists today. That does not mean that one should completely overlook the topic, however. Picking up virtual objects that *should* have some bulk about them, but don't, can quickly break the sense of immersion that certain applications are aiming for. If you cannot avoid the need to physically interact with an object in your application, then consider whether a proxy object in the real world could be used instead. For example, if you need the user to lean on a virtual surface, then bring a real-world table or similar and position it to match the virtual surface's location. The *Void* experience has used this approach to build appropriate tactile elements into sophisticated VR experiences[8].

Don't be daunted. There is a lot to consider and balance about when forming the design of an immersive application, and many of those who find themselves inspired by the potential of this technology, soon give up because the daunting complexity of getting from idea, to implementation. Whilst understandable, this stifles progress, and given the rapid spread of expertise in this area – particularly in the US, and UK – means that the skills and experience exist to guide and advise you through. If the application is important enough, help is available.[9]

References

Akiduki , H. et al., 2003. Visual-vestibular conflict induced by virtual reality in humans. *Neuroscience Letters,* 340(3), pp. 197 - 200.

Ashley, J., 2015. *Imaginative Universal.* [Online]
Available at: http://www.imaginativeuniversal.com/blog/2015/09/09/why-augmented-reality-is-harder-than-virtual-reality/
[Accessed 21 December 2018].

Ashley, J., 2018. *Imaginative Universal.* [Online]
Available at: http://www.imaginativeuniversal.com/blog/2018/10/08/magic-leap-one-vs-hololens-v1-comparison/
[Accessed 21 December 2018].

Azuma, R. T., 1997. A Survey of Augmented Reality. *Presence: Teleoperators & Virtual Environments,* Volume 6, pp. 355-385.

[8] https://www.thevoid.com/

[9] One organisation which aims to connect academics, industry, and practitioners who work with immersive technology, is ImmerseUK: https://www.immerseuk.org/.

Brinkman, W.-P., Hoekstra, A. R. D. & Egmond, R., 2015. The Effect Of 3D Audio And Other Audio Techniques On Virtual Reality Experience. *Studies in health technology and informatics,* Volume 219, p. 44.

Brinkman, W., Hoekstra, A. & van Egmond, R., 2015. The Effect of 3D Audio and Other Audio Techniques on Virtual Reality Experience. *Studies in health technology and informatics,* Volume 219, p. 44.

Case Western University, 2015. *Case Western University.* [Online]
Available at: http://case.edu/hololens/
[Accessed 21 December 2018].

Cenydd, L. & Headleand, C. J., 2019. Movement Modalities in Virtual Reality: A Case Study from Ocean Rift Examining the Best Practices in Accessibility, Comfort, and Immersion. *IEEE Consumer Electronics Magazine,* Volume 8, pp. 30-35.

Chamary, J., 2018. *Forbes.* [Online]
Available at: https://www.forbes.com/sites/jvchamary/2018/02/10/pokemon-go-science-health-benefits/#5964d1b03ab0
[Accessed 21 December 2018].

Champel, M.-L., Doré, R. & Mollet, N., 2017. *Key factors for a high-quality VR experience.* s.l., SPIE, pp. 103960Z-103960Z-12.

Dech, F., Jonathan, C. & Silverstein, M. D., 2002. *Rigorous exploration of medical data in collaborative virtual reality applications.* s.l., IEEE, pp. 32-38.

Hoffman, H. G. et al., 2011. Virtual Reality as an Adjunctive Non-pharmacologic Analgesic for Acute Burn Pain During Medical Procedures. *Annals of Behavioral Medicine,* Volume 41, pp. 183-191.

Hunt, C., 2016. *VR Heads.* [Online]
Available at: https://www.vrheads.com/tips-avoid-motion-sickness-caused-vr-gaming
[Accessed 21 December 2018].

Jones, T., Moore, T. & Choo, J., 2016. The Impact of Virtual Reality on Chronic Pain. *PloS one,* Volume 11, p. e0167523.

Lanier, J., 2017. *Dawn of the New Everything.* New York: Henry Holt and Co..

Lomas, N., 2016. *Tech Crunch.* [Online]
Available at: https://techcrunch.com/2016/01/06/oculus-rift-headset-priced-at-599-for-consumers-ships-in-march/
[Accessed 21 December 2018].

Lunden, I., 2016. *Tech Crunch.* [Online]
Available at: https://techcrunch.com/2017/02/28/google-has-shipped-10m-cardboard-vr-viewers-160m-cardboard-app-downloads/?ncid=rss
[Accessed 21 December 2018].

Maples-Keller, J. L., Yasinski, C., Manjin, N. & Rothbaum, B. O., 2017. Virtual Reality-Enhanced Extinction of Phobias and Post-Traumatic Stress. *Neurotherapeutics,* Volume 14, pp. 554-563.

Medical Realities, 2018. *Medical Realities.* [Online]
Available at: https://www.medicalrealities.com/
[Accessed 21 December 2018].

Microsoft, 2018. *Microsoft.* [Online]
Available at: https://www.microsoft.com/en-gb/hololens
[Accessed 21 December 2018].

Oculus VR, 2018. *Oculus.* [Online]
Available at: https://www.oculus.com/blog/introducing-oculus-quest-our-first-6dof-all-in-one-vr-system-launching-spring-2019/
[Accessed 21 December 2018].

Pacchierotti, C. et al., 2017. Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives. *IEEE Transactions on Haptics,* Volume 10, pp. 580-600.

Pacchierotti, C. et al., 2017. Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives. *IEEE Transactions on Haptics,* Volume 10, pp. 580-600.

Saposnik, G., Levin, M., Group, O. R. C. (. W. & Stroke Outcome Research Canada (SORCan) Working Group, 2011. Virtual reality in stroke rehabilitation: a meta-analysis and implications for clinicians. *Stroke,* Volume 42, pp. 1380-1386.

Silverstein, J. C. & Dech, F., 2005. Precisely Exploring Medical Models and Volumes in Collaborative Virtual Reality. *Presence: Teleoperators & Virtual Environments,* Volume 14, pp. 47-59.

Stanford University, 2017. *Stanford Medicine.* [Online]
Available at: https://med.stanford.edu/news/all-news/2017/02/virtual-reality-imaging-gives-surgeons-a-better-view-of-anatomy.html
[Accessed 21 December 2018].

Statt, N., 2018. *The Verge.* [Online]
Available at: https://www.theverge.com/2018/1/9/16869174/vuzix-blade-ar-glasses-augmented-reality-amazon-alexa-ai-ces-2018
[Accessed 21 December 2018].

The Body VR, n.d. *The Body VR.* [Online]
Available at: https://thebodyvr.com/anatomy-viewer/
[Accessed 21 December 2018].

Thompson, W. B. et al., 2004. Does the Quality of the Computer Graphics Matter when Judging Distances in Visually Immersive Environments?. *Presence: Teleoperators & Virtual Environments,* Volume 13, pp. 560-571.

Våpenstad, C. et al., 2013. Limitations of haptic feedback devices on construct validity of the LapSim® virtual reality simulator. *Surgical Endoscopy,* Volume 27, pp. 1386-1396.

Vive Team, 2016. *Vive.* [Online]
Available at: https://blog.vive.com/us/2016/02/21/unveiling-the-vive-consumer-edition-and-pre-order-information/
[Accessed 21 December 2018].

Vive, 2018. *Vive Blog.* [Online]
Available at: https://blog.vive.com/us/2018/11/08/htc-vive-launches-full-suite-premium-vr-offerings-businesses-sizes/
[Accessed 21 December 2018].

Wikipedia Contributors, 2018. *Wikipedia.* [Online]
Available at: https://en.wikipedia.org/wiki/Head-up_display
[Accessed 21 December 2018].