Not As Advertised: How perceptual distortion affects the metaverse vision

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ABSTRACT

Virtual reality (VR) training systems can provide consistent, repeatable, on-demand, cost-effective, and safe environments for operations in stressful high-risk tasks. However, an unrecognized risk to the value of VR training is perceptual distortion, which occurs when VR is not sufficiently representative of relevant factors in the real-world environment, particularly with respect to visual perception, proprioception, vestibular response, ergonomics, and information perception. Perceptual distortion can occur when validation efforts in VR training focus on how the training presents technical content but does not assess all relevant perceptual characteristics. VR training provides a wealth of data and interactions within a simulated environment, but distortions in the human-machine-interface alter how users understand, adapt to, and make use of this information in imperceivable ways. Without a holistic cross-over validation between real-world and virtual conditions, perceptual distortion can lead to well-practiced behaviors that are correct only within the simulation (commonly referred to as negative training). In the real-world, these automatized behaviors practiced in unrepresentative VR training could lead to catastrophic outcomes in high-risk situations. While many of these distortions can be mitigated through targeted environmental design or hardware selection, potential negative training effects must be understood and characterized, so that they can be identified and minimized before deployment. While the impetus for these effects can seem minor (user discomfort, visual perceptual alteration, misalignment between the real-world and virtual environments, misaligned ergonomic considerations, and workflow alterations), each of them could have a unique, additive, or multiplicative disruptive effects on training transfer. This paper will discuss the current use cases of VR training, perceptual and ergonomic concerns in VR not reported in simulation research, how these issues could impact training validity, and known mitigations for these issues.

ABOUT THE AUTHORS

Dr. B. Adrian Flowers, Senior Research Engineer, Aptima, Inc. has a specialization in cognition and perception in virtual, mixed, and augmented reality (XR) environments. He has leveraged this expertise in two capacities: (1) mitigation of negative physiological events in real-time systems, and (2) enhancement of human perception using a full-body approach to human augmentation. In pursuit of these goals, he has designed and executed a number of human subjects studies and used the results to develop an expanding suite of XR capabilities. These include a psychophysical study on visual and cognitive degradation in augmented reality (AR) funded by C5ISR's Night Vision and Electronic Sensors Directorate (NVESD), which was used to develop an AR remote collaboration tool for Mission Command and a Department of Transportation-funded study on the use of multimodal sensory alerting to inform the design of future roadway alerting capabilities. Dr. Flowers also has extensive experience with real-time system design, from his work with Lockheed Martin, where he was the lead software engineer, designer, and team lead on the development of a highly-connected real-time system to support submarine training. He received his PhD from University of Rhode Island, where he led studies on the detection of physiological signatures of cybersickness in the Virtual Immersive Biometry-Enabled Environment Lab. Dr. Flowers also holds an MS in computer science from University of Rhode Island and a BS in computer science from Rutgers University.

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INTRODUCTION

Live (real world) training is frequently costly and logistically challenging, demands scarce or inconsistently available resources, and involves dangerous materials and activities. Virtual reality (VR) training technologies offer the promise of more effective and efficient training; affordable, available, consistent, and safe. Further, when systems record trainee responses, they offer improved ability to provide learners with timely, accurate, complete, and objective feedback about their learning performance. When sufficiently accurate models of objects are embedded within sufficiently realistic environments and training scenarios, trainees can acquire and practice critical skills. The military faces a simultaneous push and pull for using affordable commercial-off-the-shelf (COTS) VR technologies for training. Push comes from meta-analytic results suggesting that VR training provides an effective means to deliver training results. Pull comes from commanders and training managers' goals to deliver and maintain a stock of competent and increasingly proficient warfighters in less time and at lower cost ("push training to left"). Thus, anticipated benefits are creating a drive to adapt VR technologies for all types of military training.

For this investigation, VR platforms can be defined as a combination of a visual display and the user interface. Discretization of the visual display includes monoscopic displays, stereoscopic head-mounted displays (HMDs), and CAVEs. A Monoscopic display is when a virtual environment is projected onto a screen. An example of a VR system with a monoscopic VR is a phone or tablet used to watch videos. Stereoscopic HMDs are head-worn displays that project a virtual environment to both eyes separately. Because content is projected independently across both eyes, an offset is included between the eyes to simulate binocular depth so that objects appear three-dimensional and users are able to estimate the distance to objects and their size. Examples of stereoscopic VR HMDs include the Vive Index and Oculus Quest 2. A CAVE system is a room where a virtual environment is projected onto each of the walls. Many of these systems require a user to wear goggles that are tracked by a wall mounted tracking system that enables the environment to adapt to changes in the user's head position. User interfaces for VR platforms are defined based on the type and degree of sensory feedback they replicate compared to the real-world use-case simulated in VR. These interfaces can replicate both visual, haptic, ergonomic, proprioceptive, auditory, or olfactory feedback.

VR provides an immersive, totally computer-generated synthetic reality isolated from the real physical world. VR training applications place trainees into a completely computer-generated environment that, optimally, provide presence that is indistinguishable from reality. VR can place users into hazardous or inaccessible environments and situations that otherwise are unavailable for training, while providing trainers with unprecedented control over the scenario, enabling specification of all inputs and conditions, available on demand, and consistently replicated or systematically varied.

Studies show that VR can improve many training outcomes, but where Virtual can often fail, is where it is not being evaluated. VR immerses users in a synthetic environment that can emulate the sights, sounds, and/or feel of the real-world. The approaches used to emulate the real-world do so in a way that is imperceivable to users, but that does not mean that the human perceptual system will respond in the same way that it would to the real world. These differences can distort how users respond in VR without their awareness. To better understand how VR will distort human perception, it is necessary to define the types of VR systems, how they vary amongst themselves, and how they interact with the human perceptual system.

When a VR platform is constructed to assist with training, the user must decide on what visual display best fits their use-case, what senses the UI should replicate, and the degree to which these should be replicated. The methods used to emulate each of the senses, visual, haptic, proprioception, ergonomic, auditory, and olfactory are emulated to be *good enough* for human perception, and each can introduce unique distortions that can negatively impact training without the awareness of end-users.

VIRTUAL DISTORTION

Human perception and interaction within VR can be defined as a multi-layered fidelity framework, where the layers of interest to this work are the sensory and perceptuomotor layers (Stacy et al., 2013). The sensory layer defines the understanding of information received through human visual, tactile, proprioceptive, and olfactory systems. The perceptuomotor layer focuses on the mapping of real-world motor actions and their translation within the virtual environment. VR puts users into a state of altered perception, where their ability to interpret and interact with the world becomes distorted, particularly in domains of visual and proprioceptive processing. These distortions can lead to unexpected negative training effects. Many of these potential effects are understudied, and further research is required to understand the risks that they present. While the risks inherent are negligible in a commercial space, for the armed forces, they represent potential risks to the life and safety of Warfighters. This section will discuss many of the known perceptual distortions that can occur when users are immersed in VR and their potential implications towards training and operational settings and known mitigations for them where they exist. Table 1 provides a summary and overview of perceptual distortions, prevalence, and effects, suspected causes, and mitigations.

Visual Search and Path Planning

Known causes of distortion

VR systems, particularly stereoscopic HMDs, will reduce or modify a user's field of view (FOV), which forces users to adapt by altering their visual search strategy (that is, how they scan the environment for objects of interest or threats). The normal human eye can see Approximately 95 degrees temporally (towards your ear) from the center, 60 degrees nasally (towards your nose), 60 degrees above, and 75 degrees below; this gives the average human a viewing range of 155 degrees horizontally and 135 degrees vertically. When users train to identify visual threats in VR, one must consider the impacts of training without their peripheral vision. A second consequence of a reduced FOV, is an impairment of spatial localization and navigation capabilities. Studies show that when performing active navigation tasks, individuals rely on their peripheral vision to map and update novel paths (Barhorst-Cates et al., 2016; Turano et al., 2005). Without access to their peripheral vision field, the pathways individuals take in new environments can become suboptimal due to the loss of environmental awareness. Furthermore, because users have a reduced FOV, they are required to keep more of their surroundings in their working memory, which reduces their ability to construct an accurate mental model of their surroundings.

The likelihood of users being noticeably impacted by the negative consequences of a reduced FOV are unlikely but severely understudied. The concerns in this section are based on outcomes identified in studies on navigation impairment. These studies would severely restrict the FOV of users in the real-world by restricting individuals' FOV to a total of 4° to 35°, which is severely more restrictive than is imposed by a VR headset (Barhorst-Cates et al., 2019). Without such a severe FOV restriction, researchers did not find significant differences in behavior. As such, while this may cause an impact on routing and navigation within VR, it is unlikely to be a severe or noticeable difference if one does exist, because the FOV of COTS stereoscopic displays is significantly larger than 35°. However, that makes the assumption that users will respond to a FOV identically in VR as they do in real-life, and the research does not exist to defend that claim. This leaves us with the conclusion that a reduced FOV in VR could impar visual trainee search and navigation but the severity of this impairment must be identified through further testing.

Operational and training risks

Training with an impaired FOV forces trainees to adapt to the loss of their peripheral vision while in VR. There are two potential training-caused consequences of this for operational activities: (1) trainees apply extraneous head movements learned during training (to overcome a loss of peripheral vision) when scanning a scene for threats, or (2) trainees learn to discount input from their peripheral vision, reducing their ability to respond to sudden threats in their surroundings. This presents a significant risk for VR training associated with threat detection, such as training for fighter pilots and ground combat. There are two potential mitigations for this issue: (1) use of an ultra-wide stereoscopic HMD; or (2) usage of a CAVE display.

Table 1. Summary of Perceptual Distortions

Prevalence	Potential Effects	Suspected causes	Mitigations
Balance impairment			
Understudied, prevalence is unknown Potentially higher prevalence in VR HMDs that reduce FOV	Ineffective postural training due to lack of proprioceptive cues and display rendering delays (such as parachute landing falls).	Known to occur when FOV is reduced Exacerbated by poor headset tracking (jitter)	Prioritization of quick refresh rate systems to minimize delays in positional changes.
Vergence Accommodation Conflict			
Exists in all stereoscopic VR HMDs Exacerbated by time in VR	Inaccurate human modeling of interactions due to decision making and behavior changes during VAC. Inaccurate estimates of size resulting in poor real-world applications of size estimates (such as in construction).	Deconstruction of Vergence-Accommodation Reflex	Provide center-focused, eye-tracking based, or adaptive lenses systems to simulate natural eye effects.
Spatial Misestimation			
Likely exists in all VR platforms unless explicitly mitigated	Increased injury risk due to underestimate safe operating distances.	Loss of environmental cues Potentially associated with Vergence Accommodation Conflict	Add environmental cues for better depth estimation.
Visual search & path planning alteration			
Exists whenever FOV is reduced Understudied, so the effective impact in VR is unknown	Inaccurate visual search patterns in human modeling resulting in differences compared to real world search patterns. Users may tunnel vision and limit visual searches to mitigate cyber sickness. Missed key information in decision making due to reduce view of information.	Reduced FOV / loss of peripheral vision	Utilize ultrawide FOV headsets or CAVE environments.
Haptic Cues			
Occurs whenever perceptual cues used to assess health and safety risks are not simulated	Unawareness of dangerous states usually indicated by vibrations or temperature due to lack of sensations in training (for example, system overheating).	Weak emulation of risk-adjacent perceptual cues	Provide feedback cues when a hazardous cue would occur in real world.
Ergonomic adaptation			
Occurs when using stereoscopic VR HMDs	Increased injury in operations with actual weight, torque, resistance, or posturing. Inaccurate assessments of injury risks using VR as an early ergonomic assessment tool. Increased injury risk in VR due to lack of bracing ability on physical structures.	Adaptation to ergonomic conditions of VR system	Run computer generated human modeling or live ergonomic assessments as well. Provide warnings and feedback for haptic cues that are not represented accurately.

While the majority of commercial COTS stereoscopic HMDs reduce the FOV of users, ultra-wide HMDs feature a FOV that closer matches human FOV constraints. Examples include the Pimax and StarVR headsets. It is important to note that some studies suggest that the method used to construct ultra-wide HMDs could increase the likelihood of users to experience VR sickness. A CAVE visual display, as long as the goggles do not impair the user's field of view, should also enable users to preserve their natural visual search strategies. However, a CAVE display lacks portability and represents a significant increase in the cost.

Immersion within VR could alter a Warfighter's decision-making strategies when navigation a complex environment, and can increase their cognitive load during training. Training in non-representative environments represents a great risk to Warfighters who want to rehearse operations in synthetic environments based on real-world locations. There is a risk that when Warfighters practice applying their TTPs within these non-representative synthetic environments, they learn to make decisions and determinations with an incomplete site picture. Because known causes of this phenomena include a reduced FOV, mitigations include the use of an ultra-wide stereoscopic HMD or usage of a CAVE display. There is also significant value in executing a research study to understand the risk this particular use-case presents in VR.

Vergence-Accommodation Conflict

Known causes of distortion

A visual distortion unique to stereoscopic visual displays is Vergence-Accommodation Conflict. When the human eye focuses on visual information, it performs two processes in parallel, (1) accommodation, during which the shape of the lens in the eye will change to optimize the amount of light coming from the targeted visual information based on distance, and (2) vergence, in which the eye will rotate to keep the object centered in the fovea of the pupil. Because vergence and accommodation generally happen in parallel, they are jointly referred to as the vergence-accommodation reflex.

Stereoscopic HMDs project visual information from a virtual environment to a stationary lens mounted in front of the wearer's eyes. However, this method of simulating depth interferes with the vergence-accommodation reflex. While vergence will still occur, there is no need to adjust the accommodative distance of the lens, because all virtual objects are located the same distance from the eye. This forcible disconnect of the vergence-accommodation reflex is referred to as vergence-accommodation conflict (VAC; Paulus et al., 2017). VAC is a stressful state to maintain for the ocular system, and over time can result in visual fatigue manifested in eyestrain and headaches unless mitigated. This build-up of visual fatigue over time can affect a user's cognitive state and impair their decision-making (see Figure 1).

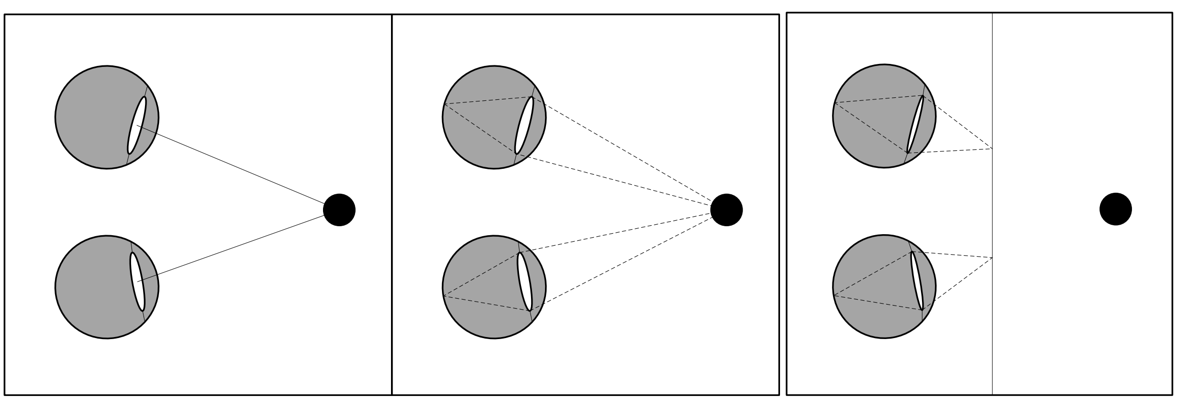

Figure 1: Vergence (left) the pupils rotated to keep an object centered on their retina; Accommodation (middle) the lens in the eye changes shape to optimize the light coming from the target object. Traditionally vergence and accommodation only occur in tandem. Eye response in VR (right) shows the conditions of a VR HMD when an object is projected to a static lens. While vergence occurs, and rotates the eyes to where it believes the object is, and the accommodative focal distance will always be the lens

Operational and training risks

VAC will induce a progressive stressor to trainees wearing a stereoscopic HMD that will led to increase cognitive and optical fatigue the longer they wear the headset. VAC is an issue inherent in stereoscopic VR HMDs, so it will always occur over time when stereoscopic VR HMDs are used. Regardless of the specifications for a stereoscopic VR HMD (FOV, resolution, etc.), a better hardware VR system cannot improve vergence-accommodation conflict issues (Vienne et al., 2020). As a result, if a stereoscopic display must be used, we should turn to dynamic, software, or environment related solutions when providing users with fully virtual or digital environments. Some stereoscopic HMD designs relieve VAC and depth estimation errors by providing lenses that adapt focus based on the object distance (Konrad, et al., 2016), eye-tracking based systems that focus based on the user's gaze (Padmanaban, et al., 2017; Stevens et al., 2018), and headset designs with greater IPD adjustment ranges (Lee et al., 2020).

Spatial Misestimation

Known causes of distortion

Users in VR are unable to properly estimate the distance or size of objects. Two reasons have commonly been identified as contributors to this distortion: (1) a loss of environmental cues in VR (such as inaccurate representation of shadows) that impairs a user's ability to make inferences regarding spatial relationships (Kurijff et al., 2010), and (2) inaccurate or missing binocular (Jamiy & Marsh, 2019), such as the consistency of cues between eyes, vergence-accommodation reflex. The degree to which users will misestimate depth and size within VR cannot be estimated, because it is dependent of the VR system; however spatial misestimation has wide-spread prevalence in VR systems and must be assumed to be inherent in a system unless explicit testing has confirmed that spatial relationships have been preserved.

Operational and training risks

VR is particularly ill-suited for testing decision-making related to spatial relationships between objects. The risk of faulty decision making caused based spatial misestimation is corroborative by driving studies which show differences in driving behavior between real-world and representative VR HMD-driven virtual environments (Blissing et al., 2019). This issue could result in negative training both when training the use of safety systems and for aviation maintenance. If unmitigated and a applied towards a safety training systems, wherein machinery may be represented and synced with machinery in the real world offering a realistic training scenario (Kaarlela et al., 2020). A lack of shadows or lighting in these environments could lead to inaccurate mental models regarding the real-world machinery's operating space, potentially leading to accidents and injury as trainees build faulty muscle memory. In an aviation maintenance use-case, by providing a hanger filled with other aircraft, tools, avatars, and environmental content, a trainee may be able to better estimate the size and depth of the aircraft relative to themselves. If Spatial Misestimation is not properly mitigated trainees may build muscle memory for non-representative use-cases.

Two popular solutions to mitigate issues related to spatial misestimation include: (1) the development of rich synthetic environments that provide tailored cues to act as points of reference, or (2) development of foveated rendering. As such, instructional designers and training developments must consider the role that depth estimation plays within the training and task needs and determine if rich environmental development, or simulation developed foveated displays are necessary to ensure accurate training transfer. By providing simulated real-time foveated rendering, additional cues such as defocus blur that our eyes can produce natural, provides some indicators of close and near objects. Usability analyses with these systems have demonstrated the ability to reduce depth perception errors by 27% (Hussain, et al., 2020). Applying these visual effects can improve performance requiring depth perception even if users do not perceive it to be assisting performance (Cidota et al., 2016). Similarly, rich environmental cues can also help with depth estimation as users are able to use different objects within the environment as depth cues (Vienne et al., 2020).

Balance Impairment

Known causes of distortion

Balance is a combination of input from the visual and vestibular systems. As individuals age, they rely more on input from their visual system to balance, as compared to signals from their vestibular system (Anson et al., 2017). Similarly, studies suggest that when in VR, input from the user's visual system may become less reliable than their vestibular system (Imaizumi et al., 2020). Corollary, studies on peripheral vision suggest that users rely heavily on their peripheral vision to maintain balance during standing tasks (Anson et al., 2017; Melzer, 2017). As such, while under investigated, there is a likelihood that a reduced field of view in VR can reduce the stability of users. Similarly, studies on VR sickness have found that when a stereoscopic HMD does not have accurate tracking (typically when the headset display jitters), users can exhibit increased sway, suggesting a decrease in the user's stability. Consequently, actions in VR reliant on maintaining and assessing balance are potentially unreliable. The prevalence of this issue unknown because the underlying mechanism of this distortion is understudied, however the severity of this issue when it does occur is known. Studies on balance in VR rely on standing tests, and agree that an individual's balance in VR is not worse than their balance when their eyes are closed (Imaizumi et al., 2020). It is unknown whether the severity of balance alterations in VR are consistent when the individual is in motion.

Operational and training risks

Depth perception issues, rendering delays, and balance issues in VR make it a riskier option for rehabilitation and physical therapy which could lead to ineffective medical treatment (Baniasadi et al., 2020). Consideration the targeted and precision movements needed for effective physical therapy it is clear why VR may make physical movement training ineffective. In the miliary domain, this may be of great concern for training systems such as parachute trainers that are highly impacted by the trainee's posture during free fall, parachute deployment, steering, and parachute landing falls. It is critical to positioned in the right way, flex muscles in the correct manner, and land accordingly to prevent an injury in these operations. Even if we are able to make a perfect synthetic replica of the environment, weather, and parachute physics, the trainee will still need to rely on proprioceptive feedback from the body in order to train effectively to prevent injury.

Ergonomic Distortion

Known causes of distortion

For many higher-end virtual reality systems, users are still tethered via cables to high end computers. Users will have to compensate or move carefully to avoid damage to cables with additional weight or resistance to each movement. For lower-end virtual reality headsets, users are limited to non-representative controllers to interact with the environment. Using controllers (coupled with depth perception issues) can result in longer interaction times as well as prolonged periods of time holding and grips the controllers in each hand. Fatigue and discomfort can occur at even short periods of time depending on the design of the headset. Additionally, normal comfortable interactions may not be feasible within the VR environment. When performing maintenance in tight or awkward locations, the user is unable to rely on bracing or leaning tactics to minimize strain on body parts (Reinhard et al., 2020). When working for extended periods of time, a maintenance worker may brace their elbow along a frame or their back against a wall. Not only can this lead to unnecessary strain for the user, it can also lead to inaccurate evaluations of the user injury risks.

Due to the additional weight of head-mounted VR systems, users can experience discomfort when tilting their head or may even refrain from doing so. Particularly for children, the development of the body and perceptual systems affect how they position themselves in VR. At a younger age, children rely more on visual systems as opposed to proprioceptive and vestibular information and attempt to compensate for posture mismatches by exaggerating head movements (Miehlbradt et al., 2021). Interaction and depth perception issues could cause exaggerated movements by users in attempts to mitigate perceptual issues in VR. The additional weight from the headset can also change the way in which trainees are positioned when interacting with the environment. For virtual reality systems that do not track head movements geospatially, users may need to extend their arms further than they would in reality in order to reach an object. In many instances, we chose to lean forward and reach a moderate distance in order to pick up an object out of reach, but with virtual reality systems that do not allow have geospatial capabilities, leaning forward does not bring the user closer to objects in the environment. Users may then need to stretch their arms out to full extension or even twist their torso order to reach objects out of reach. As a result, users may learn incorrect posture when working with heavy machinery or be unrepresentative for human evaluations using digital twins.

Operational and training risks

The largest concern for ergonomic distortion for VR training with digital twins are the increased risks related to injury. We previously explained how visual distortions, cybersickness, and different interaction methods mean that interacting with a digital twin is not a 1-to-1 comparison with a real-world system. The motions and cues learned in VR can be impacted by this distortion leading to incorrectly learned posture, positioning, and movements that could increase risk of injury or error when applied to real-world operations. For example, a designer may use a simulated environment with a digital twin to assess if an aircraft design provides sufficient workspace for maintenance procedures. However, distortions in the digital twin may not be sufficiently precise to determine whether a mechanic would have sufficient clearance to avoid injury. As digital twins are used to assess how humans interact with systems that subsequently guide design, considerations must be made to the way these interactions change when within VR (da Silva, Mendes Gomes, & Winkler, 2022). Until VR systems provide naturalistic interaction methods, lighter weight untethered connections, and minimal visual distortions, a subset of real-world evaluations should also be conducted to verify the accuracy of VR-based conclusions. Designers should run digital twin assessments in tandem with computer generated human modeling or with smaller subset of live ergonomic assessments.

Haptic Distortion

Known causes of distortion

Haptic distortion can occur when we anticipate texture, vibrations, torque, resistance, weight, pressures, temperatures or other sensations when interacting with objects within the environment. These combined tactile sensations provide feedback and warnings about physical objects with which we interact. Almost all currently available virtual reality systems lack any haptic information. Without this key information, VR-trained activities may lead to inappropriate physical actions in what ways to tense, flex, or move our bodies in order to prevent injury. In some instances, even attempting to simulate haptic feedback can be ineffective in comparison to real-world haptic cues (Våpenstad et al., 2017).

Haptic Distortion Impacts

Operational and training risks

Haptic distortions within VR digital twin environments can lead to poor transfer of training. Some examples could include: (a) temperature mismatches (and the lack of ability to sense heat in the surrounding space) can lead to burns or inaccurate assessment of system states, (b) inaccurate representation of texture may lead to faulty decisions about whether particular parts remain serviceable, (c) lack of pressure feedback may result in inaccurate assessments of the strain the task can put on in an individual, and (d) weight mismatches could result in injury or equipment damage if trainees discover the actual weight of a component when, for the first time, they remove the final bolt supporting the heavy real-world counterpart of its virtual replica. Weight related lack of haptic feedback can be exacerbated when virtual training removes panels, bolts, and parts entirely once the trainee interacts with the part in VR with the virtual tool which can put the users at risk of falling parts and potential blunt force trauma. For pressure-related VR training with digital twins of aircraft in flight or space operations can fail to provide cues to trainees on proper muscle responses. As we attempt to make digital twins of aircraft, we must consider and model human flight inputs and behaviors, however without normal tensing that occurs with g-force maneuvers, these digital twins may be utilizing inaccurate flight modeling data. In these cases, utilizing pressure feedback or warnings in the VR environment to trainees about muscle strain behavior being too little or too great could provide more accurate training and data generation.

Torque and resistance feedback can lead to inaccurate assessments if parts are properly installed, as many maintenance and installation procedures require the use of a calibrated torque wrench tool that produces “click” that the user hears and feels in through the tool when correct torque is achieved. Without the feedback of that in the real world, it is possible that maintenance errors could lead to system malfunctions, incidents, or failure. The lack of this resistance in assembly domains can lead to inaccurate simulations of the tasks users carry out (Reinhard et al., 2020). We often use cues such as temperature and vibrations to tell when something is not operating properly. For example, drivers of cars can recognize a feeling that the car has changed that can indicate low tire pressure or engine overheating. When training in a virtual simulated car without these indicators, it may lead to risk or injury. For temperature and without any training providing ranges of “acceptable” temperatures, a trainee may be unable to assess if machinery is overheating. Not only could that run the risk of system malfunction and accidents, the damage of operating machinery while overheating may cause costly and irreparable damage. Attempting to provide simulated haptic feedback in VR surgery training has even led to negative transfer of training (Våpenstad, 2017). With the current state of haptics in VR, providing feedback cues when a hazard would occur in real world is a beneficial alternative. Training environments can provide prompts when a user would need to check for cues such as vibrations or temperature before handling a system. If users fail to do so, providing representations of repercussions (e.g. images of likely injury) can be a strong reinforcement tool when haptics are not feasible or effective. Ultimately, researchers and developers should continue to research methods to provide realistic haptic feedback and note limitations to real-world operations in the meantime.

CONCLUSION

VR has clear benefits in the world of VR training and digital twins for providing low-cost training, evaluating novel systems, and guiding design decisions. However, technology is not yet sufficiently advanced to completely replace real-world training experiences. Due to the way we humans perceive the world around us and limitations of current technology, distortions in the virtual world are inevitable. We present ways in which VR results in visual, vestibular, decision-making, haptic, and ergonomic distortions as well as the primary causes. Additionally, ways in which each distortion can impact the effectiveness of training and evaluation applications are also presented. While there are some software and hardware mitigations, there is still a great deal of research to be done to identify when and how to improve the ability of VR to mimic the real world. The potential solutions to each distortion discussed here and presented within the appendices are not exhaustive but aim to provide an overview of considerations when applying VR in training and simulation applications. VR has the potential to provide unparalleled benefits and must consider human perception at its core to truly achieve an indistinguishable reality.

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