

# **Situational Awareness Methods in Virtual Reality Training: A Scoping Review**

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## **ABSTRACT**

In 2020, the US Military budget for Air Operations Training increased by \$197.7m to accommodate additional virtual training, instructor pilots, and air support. These virtual trainers are essential for preparing warfighters for scenarios that are rare, dangerous, and complex. While virtual training has historically been conducted in costly and immobile “big box” simulators, they can now be deployed using consumer-grade immersive virtual reality (VR) head-mounted displays (HMDs). For example, Air Force maintenance airmen use VR HMDs to train on the C-130 due to savings of time and money over live training, without loss of training effectiveness. However, one challenge when using an HMD for training is giving the instructor complete awareness of what the learner is doing both in the virtual environment. Typically, instructors observe a learner’s progress in a simulation from a monitor that provides a window into the virtual environment. This window is missing affordances for interaction that make communicating with the learner difficult. The challenge of the instructor and learner’s different access to the virtual environment, and the resulting lack of situational awareness, can cause a disruption in communication and degrade learning outcomes. The authors propose that this could be mitigated using a number of techniques from existing research. This paper provides a scoping literature review to explore five potential solutions: asymmetric, symmetric, asynchronous, substitutional, and adaptive VR training systems. The authors evaluated each of these innovations in VR collaboration for its impact on 1) instructor-learner workspace awareness and 2) communication in VR simulations to guide industry and interservice training professionals. Results show that each of the current VR collaboration techniques has strengths and weaknesses, and understanding these trade-offs is crucial to derive the maximum benefit for a specific training task.

**Keywords:** Virtual Reality, Training, Asymmetric Technology, Substitutional Reality, Communication

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## **INTRODUCTION**

Virtual Reality (VR) technology is seeing an increase in adoption for training applications since the release of consumer-level Head-Mounted Displays (HMDs) like the Oculus Rift and HTC Vive. These systems make high-quality VR simulations portable and affordable for the first time. The US military was quick to take notice and has invested heavily in VR HMDs and other simulation technology to train their warfighters. In 2020, the US Military is increasing spending on Air Operations Training by \$197.7 million to accommodate additional virtual training, instructor pilots, and air support (Office of the Under Secretary of Defense, 2019). More and more frequently, this includes VR solutions such as HMDs for training C-130 airmen (Stancy Correll, 2020). Research and practical applications have shown that this technology can be extremely effective for training purposes while reducing the resources needed to conduct it (Boud et al., 1999; Kaplan et al., 2020; Lele, 2013). One way that VR HMD training can be improved is by enhancing situational awareness between the instructor and learner, e.g., a warfighter.

Current VR HMDs can impede natural communication that is essential to situational awareness and the learning process (Seymour et al., 2002). For example, the learner may not be able to hear important feedback from the instructor over sounds in the Virtual Environment (VE). Similarly, the instructor cannot see the VE in the same way as the learner, because they are often not using an HMD to view the simulation. Augmented Reality (AR) HMDs can yield similar situational awareness problems if the instructor is not also wearing a headset. All of these examples contribute to a decrease in situational awareness and loss of communication that can result in decreased learning outcomes. As a result, a learner may need to repeat training, perform more training, or go into the field unprepared. All of these consequences result in potential danger to a warfighter and/or additional time and resources to correct. This paper analyzes potential solutions to improve situational awareness of the instructor and learner during VR training applications and optimize the learning process using a scoping review. Scoping reviews are important for identifying and clarifying key characteristics and concepts, as well as gaps in the understanding of both (Munn et al., 2018). By categorizing and characterizing potential solutions from existing VR training literature, this research can recommend key areas of future study into bridging the situational awareness gap. The current scoping review is a necessary step to ensure that future research on the topic of virtual reality training focuses on viable solutions to situational awareness and yields positive training outcomes.

The following section presents a brief review of the history of simulator and VR training, followed by an inspection of the communication needs of the training group and their delivery channels. Next, the methodology of the review, and an analysis of the corpus will be delineated. Then the authors will describe the interaction themes uncovered during the review and relate these themes to training needs. Finally, other considerations that were revealed, as well as those areas that require future investigation will be addressed.

## **BACKGROUND**

In this paper, the authors will examine the instructor-learner communication paradigm in the context of using a VR HMD and make recommendations on how to facilitate effective communication between an instructor and learner during VR training based on examples from existing peer-reviewed literature. The following subsections will discuss relevant background information on VR simulation and training and situational awareness. This information will show how VR HMDs can inhibit key communication channels between the instructor and the learner and negatively affect learning.

## **VR Simulation and Training**

VR is often thought of as one point of a continuum between reality and virtuality (Milgram et al., 1995). VR lands nearer to virtuality on this spectrum, meaning that the majority of the environment experienced by the user is computer-generated. This ability to create virtual environments (VEs) for training has revolutionized the world of training for scenarios that pose a high-risk or are expensive to recreate in real life.

The development of the Link Flight Trainer in 1931 (Link Jr., 1931) marks the beginning of VR training. This novel machine allowed pilots to learn to “fly by instruments,” providing accurate physical and instrument responses to the pilot’s input, all while remaining safely on the ground. Many consider this the first example of virtual reality hardware. Since then, new hardware has been developed to accommodate a wide variety of VR applications.

Some VR training systems have used traditional computer displays for their training environments. However, these systems typically do not allow the user to see the environment in 3D, nor do they promote embodiment, or sensorimotoric engagement with training content, which has been identified as important to understanding and learning new content (Johnson-Glenberg et al., 2014). To allow embodied interaction with VR content, training systems can use CAVE Automatic Virtual Environments (CAVEs), which project stereoscopic images on large wall-like screens (Cruz-Neira et al., 1993). Yet another method is to use HMDs to present VR content. Each of these methods has its trade-offs such as cost, portability, and image quality that make them suitable for different VR training applications. However, in 2016, a new generation of VR HMDs was released by Oculus and HTC. These devices greatly improved upon the resolution, form factor, field of view, and price of earlier HMDs and made them a popular choice for VR training.

VR training has been used in a variety of contexts from air traffic control (Zachary et al., 1999) to training team skills (Ostrander et al., 2019). Some early HMD research also pointed to the ability of VR to reduce training time for tasks such as manual assembly and maintenance when compared to training using engineering drawings (Boud et al., 1999). Similarly, Seymour et al. found that VR training for a surgical task led to faster and more accurate procedures when compared to a control group who did not practice the procedure in VR (Seymour et al., 2002). VR HMDs showed promise as a tool for military training, not only because of their effectiveness (Kaplan et al., 2020) but also because of their unique ability to simulate dangerous wartime scenarios in a controlled way (Lele, 2013). For these reasons, the U.S. Military has put its trust behind simulator and VR training by investing millions of dollars toward their implementation (Office of the Under Secretary of Defense, 2019). Therefore, it is imperative that VR training is optimized to increase readiness and the efficacy of the warfighter.

## **Situational Awareness in VR Training**

Situational awareness is an important component of decision making across a variety of contexts, including aircraft control and piloting (Endsley, 1995). In such contexts, as the novice learner is exposed to the virtual environment, the expert instructor needs to maintain situational awareness of the shared environment to offer targeted feedback and assistance (Gutwin & Greenberg, 2000). Such situational awareness is referred to as *workspace awareness*, or “the up-to-the-moment understanding of another person’s interaction with a shared workspace... [which] involves knowledge about where others are working, what they are doing, and what they are going to do next” (Gutwin & Greenberg, 2002). The shared workspace in a training environment supports the cooperative task that composes the joint process of teaching (for the instructor) and learning (for the learner) the task being trained.

Proper mediation of communication is important for forming workspace awareness (Dourish & Bellotti, 1992; Gutwin & Greenberg, 2002). Mediation of communication is essential for coordinating remote use of technology, but it can go overlooked in co-located use of technology. When working face-to-face, a team can typically communicate and orient themselves to observe one another’s actions in order to maintain workspace awareness (Gutwin & Greenberg, 2000). When using an HMD, however, the learner’s senses are immersed in the VE, thus rendering computer mediation necessary – even when both users occupy the same physical space (Kraus & Kibsgaard, 2015). In HMD-based training, workspace awareness cues, such as gaze-direction indicators, must be incorporated into the VE. Such cues support the gathering of workspace awareness information. The instructor needs to be able to monitor the learner

and be able to make moves to offer assistance when necessary, while the learner needs to be able to monitor the instructor, in turn (Gutwin & Greenberg, 2002).

In many cases, this feedback from instructors is essential to the learning process. Kruglikova et al. (2010) found that surgical students who received instructor feedback in addition to VR simulation training achieved proficiency faster than those without instructor feedback. However, the use of HMD hardware can often inhibit communication between the learner and instructor, not only because the learner cannot see the instructor but also because they are experiencing two completely different realities.

Previous research into computer-mediated communication has organized the interaction methods along several axes, most popularly along the axes of time (*synchronous* vs. *asynchronous*) and place (*co-located* vs. *remote*) (Johansen, 1988). Additionally, Benford and colleagues (1998) use a multidimensional view of the virtuality-reality continuum (Milgram & Kishino, 1994) to describe “mixed-realities,” or blended reality. In blended reality, two spaces (such as a VE presented in an HMD and the external world) are merged by a window (such as a computer monitor) at their boundaries. In their paper, they identify that communication is important to maintaining awareness in these asymmetric environments.

A typical VR HMD training configuration consists of a learner using an HMD and tracked controllers accompanied by a co-located instructor viewing the VE via a computer monitor, which serves as a window into the VE. This asymmetric experience can inhibit natural communication between the learner and the instructor because the HMD obscures many of the typical human-human communication channels (visual, auditory, and using media). Additionally, Kraus and Kibsgaard (Kraus & Kibsgaard, 2015) noted that computer-mediated communication methods are often of lower quality than unmediated methods. For example, computer-mediated auditory communication often suffers from low sound quality and latency. In contrast, computer-mediated visual communication can result in higher latency, reduced field-of-view, as well as limited stereo depth and color range. Therefore, natural communication is ideal for training, because it allows for the most situational awareness and highest fidelity. Training methods that do not support natural communication (alone or in addition to computer-mediate communication) risk barring critical feedback from the instructor and limiting the associated training benefits.

Table 1 shows the four communication channels typically used in a VE and how they can be transmitted (natural, computer-mediated, or a combination of both) in various co-located training configurations. To create this table, the authors evaluated the communication capabilities of off-the-shelf VR and AR hardware available before June 2020. Each training configuration was evaluated for its capabilities across four key communication channels: visual, auditory, haptic, and using pre-recorded media (Kraus & Kibsgaard, 2015). The VR and AR training configurations were then juxtaposed with traditional co-located classroom training on the left of Table 1, and distributed online training on the right. These configurations represent fully natural communication and fully computer-mediated communication scenarios, respectively.

Additionally, online communication inhibits the use of haptic communication completely under most circumstances, and is, therefore, represented by “N/A” in Table 1. Table 1 shows that AR HMDs and VR CAVEs both facilitate natural communication in all four channels in addition to computer-mediated communication in some channels (as noted by the presence of both icons); these hardware configurations do not inhibit communication at all. AR HMDs and VR CAVEs can augment communication by providing new ways to communicate visually, using media, and, in the case of an AR HMD with tactile controllers, through haptics.

The ability to combine both natural and computer-mediated communication makes AR HMDs and VR CAVE systems powerful tools for training at the expense of presence, price, and mobility. Contrastingly, VR HMDs facilitate computer-mediated communication in all four channels, but they cannot provide natural communication visually or when using media. Such a disconnect can be detrimental to the overall communication experience when using VR HMDs because natural human-to-human communication requires great detail and typically takes place using multiple channels simultaneously (Kraus & Kibsgaard, 2015). Indeed, it is important to mediate channels that would otherwise be occluded for both learners and instructors during VR training using an HMD.

**Table 1. Matrix of natural and computer-mediated communication channels in various co-located training configurations.**

Communication Channel	Training Configurations				
	Classroom	VR CAVE	AR HMD	VR HMD	Online *
Visual		/	/		
Auditory			/	/	
Media (pre-recorded)		/	/		
Haptic			/	/	N/A

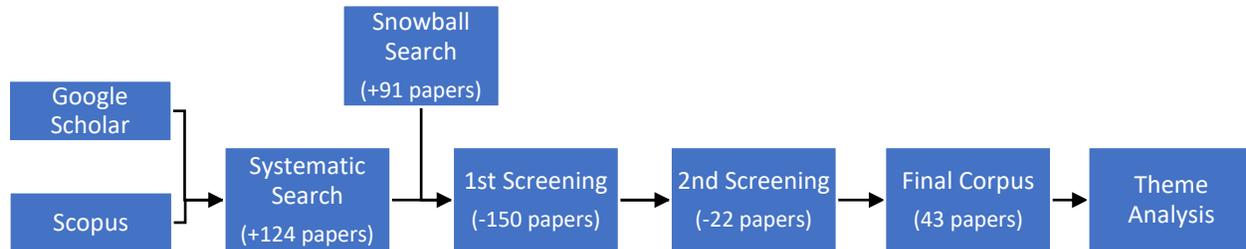
= natural communication

= computer-mediated communication

\* The online training configuration describes a distributed instructor and learner

**METHODS**

For the scoping review, peer-reviewed papers exemplifying methods of interaction between immersed and external HMD users relevant to VR HMD training were gathered following a systematic method (Figure 1). To curate an overview of the topic area, the final corpus (a collection of papers) was sorted into themes, as described in the text below. This section will describe the research process in detail.



**Figure 1. Flowchart describing the combined approach to the formation of the corpus of papers.**

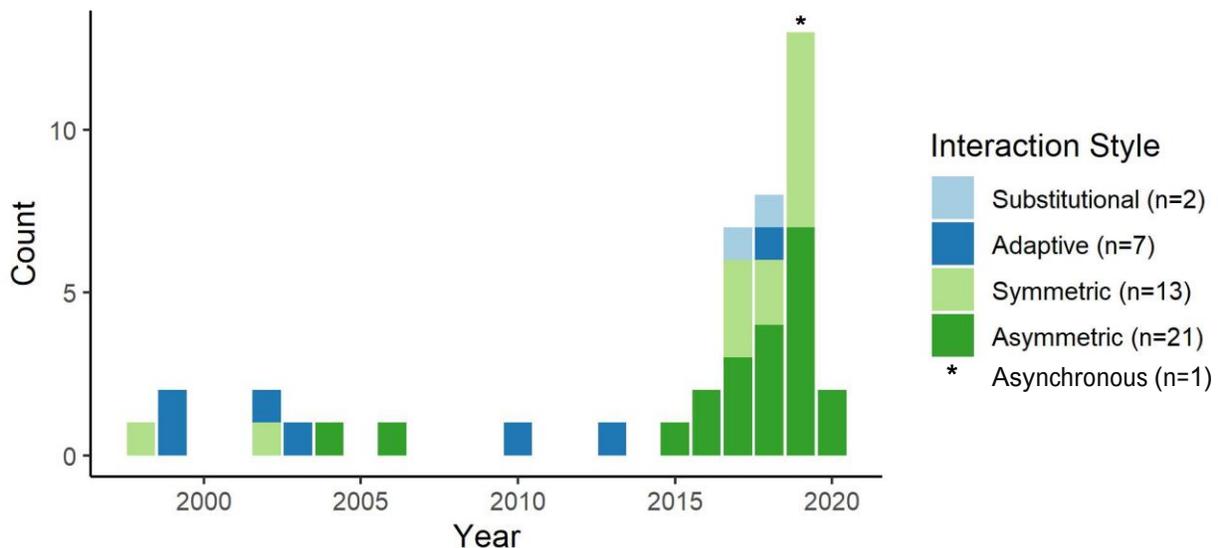
Using Scopus to retrieve published works, searches were limited to articles on adult humans published in the English language. The database was searched using a VR term (‘Virtual Reality’ or ‘VR’ or ‘Mixed Reality’ or ‘Head-Mounted Display’ or ‘HMD’) AND a collaboration term (‘collaborati\*’ or ‘asymmetric technology’ or ‘cooperati\*’ or ‘bystander’ or ‘multiple head-mounted displays’ or ‘multiple HMDs’ or ‘multi-user’ or ‘multiple user’) OR a location term (‘co-located’ or ‘collocated’ or ‘shared space’ or ‘same space’). A second search used Google Scholar to identify papers with adaptive systems terms (‘adaptive’ or ‘adaptive system’ or ‘intelligent tutor’ or ‘intelligent tutoring system’ or ‘computer assisted instruction’ or ‘informed virtual environment’) and VR training terms (‘Virtual Reality’ or ‘VR’ or ‘Mixed Reality’ or ‘Head-Mounted Display’ or ‘HMD’ or ‘simulation’ or ‘serious game’ or ‘virtual learning environment’).

To be included in the corpus, the articles were required to meet the following inclusion criteria: (i) include the use of an HMD, (ii) discuss communication or awareness and/or include a facilitator role in conjunction with HMD use, and (iii) discuss or test co-located use of said HMD or collect data at the level of the individual or group (i.e., not be a review, extended abstract, or workshop proposal). It should be noted that because simulator training and education are traditionally delivered face-to-face, the focus of this review is on co-located use of VR HMD training. Additionally,

while HMDs prior to 2014 (when the Oculus Dev Kit 2 was released) were lower quality in terms of refresh rate and field of view and were less affordable than HMDs developed more recently, the year was not an exclusionary criterion in this survey. Insights from relevant articles over six years old are carefully extracted, taking care to caveat performance concerns while maintaining the findings relevant to group function in the co-located use of VR HMDs.

Using the keywords, the researchers identified 124 articles between December 2019 and April 2020. An additional 91 articles were identified and were added to the corpus through follow-up snowball searches based on the reference lists of relevant articles. Next, abstracts and titles were used to determine whether each article met the inclusion criteria. After this first screening, the corpus included 65 articles that were eligible for continued review. After applying the relevant exclusion criteria each paper's body in the second round of screening, the corpus totaled 43 papers spanning just over 20 years.

A valuable output of a scoping review is the list of themes that emerge from the analysis of the corpus. These themes aid the analyst in understanding the history of research in the field and often point to research gaps that need to be addressed in the future. Analysis of the corpus of papers resulted in five themes. Three themes were grounded in prior literature (introduced in the Background section, and discussed below) relating to computer-mediated communication and training: *asymmetric VR*, *symmetric VR*, and *adaptive VR*. Two were emergent themes: *asynchronous VR* (after-action review) and *substitutional VR*. Figure 2. The distribution of identified themes by publication year. Asynchronous is double-counted, representing an asymmetric, asynchronous VR interaction style. shows the count of studies categorized under each interaction style (identified themes) over the years.



**Figure 2. The distribution of identified themes by publication year. Asynchronous is double-counted, representing an asymmetric, asynchronous VR interaction style.**

Based on the literature surrounding VR use in training and computer-mediated communication, the authors began the review with three thematic categories, or themes, pertaining to interaction styles that can be used to expand instructor situational awareness in VR. *Symmetric VR*, or the use of the same technology by all parties accessing a single virtual environment, can be considered opposite *asymmetric VR*, which incorporates different devices into the collective experience. These categories are related to the work of Benford et al. (1998). They discussed ways to join mixed-realities at their boundaries and noted the impacts of improperly mediated asymmetric experiences on awareness. *Adaptive VR* systems use a feedback loop to change the system state (such as the VE) based on a stimulus (such as the user input) (Kelley, 1969). This automatic adaptation can reduce the need for workspace awareness on the part of the instructor while still providing customized feedback for the learner (Vaughan et al., 2016). Intelligent Tutoring Systems (ITSs) are a subset of adaptive systems that are used to customize learning feedback (Rickel & Johnson, 1997). ITS can be paired with VR training to create an adaptive Virtual Learning Environment and limit the need for instructor-learner communication, freeing up instructor time for other tasks, or potentially enabling them to instruct multiple learners simultaneously.

The remaining two themes were either new or unexpected, based on previous literature. *Substitutional VR* is a way to provide the details of the VE to non-immersed users (such as instructors) by aligning the physical space with the virtual workspace both by carefully matching virtual objects to their physical counterparts and projecting the VE onto the tracked space (Zenner et al., 2018). Substitutional VR is, therefore, a form of asymmetric VR, but it is separated because of its attention to passive haptics by the incorporation of the physical environment in the VE. The final method of VR HMD use which emerged during the review is known as *asynchronous VR*. While Johansen's (1988) framework included time (synchronous vs. asynchronous) as one way in which computer-mediated communication may be used, the recording of VR experiences to be consumed later (e.g., asynchronously) in VR is not yet a ubiquitous interaction technique and was not originally included as a theme. However, after identifying one such experience, the theme was added. The following sub-sections will summarize how each of these interaction styles in VR training attempts to solve the instructor-learner communication gap and increase situational awareness when using VR HMDs.

## RESULTS

This section will summarize the research on co-located HMD interaction and how these innovations tie into VR training. Specifically, the authors define the five themes of interaction styles in co-located VR (asynchronous VR, symmetric VR, asymmetric VR, substitutional VR, and adaptive VR) and offer insights relevant to conducting HMD-based training using each specific interaction style. Each of the first four themes describes methods that are meant to replace the original method of using a computer monitor as a window into the VE. The final theme, adaptive VR, is a method that can be paired with either the existing window-into-the-VE method or any of the other interaction styles to ameliorate the instructor's awareness.

Within this section, citations are representative of the literature belonging to any specific theme. The full corpus of papers is located in a public Mendeley library at <https://www.mendeley.com/community/trainer-situational-awareness-methods-in-virtual-reality-a-scoping-review/>. After presenting each interaction style in turn, the final section includes an interpretation of the state of the field for VR training and offers future directions for research in this area based on the findings of this review.

### Asynchronous VR

One method of VR HMD use, which emerged during the review, is known as *asynchronous VR*. Johansen's (1988) framework, which is famous in group-based computer interaction circles, included place (remote vs. co-located) as well as time (synchronous vs. asynchronous). However, the recording of VR experiences to be consumed later (e.g., asynchronously) in VR is not yet a ubiquitous interaction technique. Chow et al. (2019) introduced a method for viewing previously recorded virtual interactions, wherein a learner could watch an expert's action in first-person view using an HMD of their own. Asynchronous VR is reminiscent of the after-action review from training literature (Zachary et al., 1999), as it could allow the instructor to join the learner in VR after the training has ended so that they may better illuminate the actions which require feedback. Another study that focused on the simultaneous review of 360-degree VR film used techniques such as view-locking to aid the group in workspace awareness (Nguyen et al., 2017). While that study focuses on the synchronous use of headsets, thus excluding it from the thematic area *asynchronous VR*, the interaction could be a useful method for after-action review, where the instructor guides the learner to observe and learn from their actions. Naturally, there are time costs to the described methods within this interaction style. The remaining themes describe the synchronous use of VR HMDs.

### Symmetric VR

Introducing a second HMD comes with new challenges. First, safety should be a priority (Lacoste et al., 2017). In some training scenarios, the learner may be completely stationary, allowing the instructor to move around without worry; however, tracking errors may cause misjudgments of distances that could result in tripping or other accidents. Second, workspace awareness can be difficult to maintain. Visual cues are difficult to display accurately in VR (Nguyen et al., 2017), and without external motion-tracking technology, current algorithms can only approximate arm and leg positions. Relatedly, if there is any real-world aspect to the training, such as a mocked-up controls interface used as a prop to afford passive haptics, the instructor loses awareness for learner interactions with the prop when they enter an HMD. There are also limits to note-taking in VR, which need to be overcome for immersion to be truly useful

in this situation (Nguyen et al., 2017). Lastly, verbal communication may be impacted when both training users are wearing VR HMDs, especially if they are required to use microphones rather than natural audio communication since this can introduce disruptive sound feedback-loops and echoes.

### **Asymmetric VR**

The third theme is that of Asymmetric VR. Asymmetry can be used to encourage interdependence and to cater to the diversity of interaction preferences or needs (Gugenheimer et al., 2017). If two users of a shared VE have different goals, asymmetric VR can be used to reduce the cognitive resources needed to accomplish each user's goal by offering an interface that is tailored to those specific goals. For example, when used in therapeutic settings, the therapist and client have different requirements for effective interactions with the VE that can be supported by the therapist using peripheral interfaces, such as an interactive tablet, while the client is immersed in an HMD (Elvezio et al., 2018). Other authors use different interactions such as showing third-person views and giving external users touchscreen portals to the VE to aid in film design (Henrikson et al., 2016) and exploratory data analysis (Cavallo et al., 2019). By introducing a small screen tied (via code) to a tracked VR controller, Gugenheimer et al. (2017) create a series of VR games that provide engaging, high-presence experiences to non-HMD users of the environment. At the same time, these experiences provide position information which increases HMD-user awareness of outsiders, such as the instructor during HMD-based training.

Asymmetric VR is a clear contender for VR-based simulation training environments, due to its demonstrated ability to increase awareness of the virtual world (Chan & Minamizawa, 2017) and its alignment with the naturally dominant position of the instructor (Gugenheimer et al., 2018). Additionally, these innovations can aid in the spread of VR in the education context, offering options for the simultaneous awareness of multiple users at once, without necessarily immersing more participants into a shared VE (Chan & Minamizawa, 2017; Thomsen et al., 2019). With proper implementation in training, innovations in asymmetric VR could facilitate the embodied learning needs of the learner while also providing the instructor with the tools they need to deliver effective feedback.

### **Substitutional VR**

Like other forms of asymmetric VR, substitutional VR is a way to provide the details of the VE to non-immersed users (such as instructors). What sets this form of asymmetric VR apart from the others is that it also aligns the physical space with the virtual workspace by carefully matching virtual objects to their physical counterparts (Zenner et al., 2018), thereby bringing the physical world and the virtual world closer together. Substitutional VR, therefore, forms its own emergent category in the analysis of the corpus. In substitutional VR, objects in the physical space that may have previously needed to be pushed to the edge of the room can be incorporated as parts of the VE (i.e., as a prop for passive haptics on a virtual table). To increase the engagement for HMD-outsiders (such as the instructor), a projection of the VE on the real space can make the tie between the two worlds more visible. In training, projection-based VR can be combined with immersive VR (as in Ishii et al., 2017) to allow an outside view of the world within the HMD without sacrificing the instructor's awareness of the physical world.

### **Adaptive VR**

Contrasting with many of the other methods presented here, Adaptive VR does not require additional hardware and can be used to take on some of the workload of the instructor. The distribution of awareness responsibility can lessen the need for instructor-learner communication. Additionally, instructors may have different methods of intervening during training, based on their experience and preferences (George et al., 2019). Adaptive systems can help eliminate biases and effects caused by these individual differences by interrupting training more consistently.

The adaptive VR literature exemplifies two main methods that ITS can be used to communicate personalized training information to the learner in VR. The first method is using adaptive virtual agents. These virtual agents can serve multiple roles in the simulation, including an instructor, but also members of a virtual team working alongside the learner (Querrec et al., 2003). The system senses the student's learning state and adapts the feedback given by the virtual agent to their needs (Rickel & Johnson, 1999). The second and more prevalent method is adapting the training content itself. This method involves adapting the difficulty of the subsequent task based on the user's performance

during previous tasks (Barzilay & Wolf, 2013; Matsubara & Yamasaki, 2002). Self-adaptive systems are those which make these adaptations completely based on a learning model with no input from the instructor (Ropelato et al., 2018). Other systems keep the instructor in the loop by suggesting adaptations but keeping the impetus to intervene with the instructor (Ćosić et al., 2010). Though previous research in adaptive VR technology has shown that these systems are viable, few have evaluated their effectiveness when compared to traditional VR training. More research should be done to compare training transfer when ITSs partially or fully replace human instructors.

Furthermore, adaptive systems have the potential to be used to mitigate comfort, safety, and usability problems that are outside of the typical scope of ITS. In a VR training scenario, the instructor also serves roles that indirectly affect learning, such as showing the student how to use the VR hardware and helping them avoid collisions with environmental obstacles. These roles are not fulfilled by ITS, but other adaptive systems could be implemented to help solve these problems in VR. For example, an affect-aware adaptive system could detect and adjust to physiological symptoms of negative emotions and stress in VR (Saha et al., 2017). More research should be done to investigate other applications of adaptive technology on VR training.

## **DISCUSSION AND CONCLUSIONS**

This paper has presented five co-located VR interaction themes that have been identified from a comprehensive literature search as potential methods to mitigate communication and shared workspace awareness problems in VEs. These interaction styles are useful for the transition to HMD-based VR training. By providing training in VR, and especially with responsive avatars that allow embodied interaction, more effective learning gains can be realized (Johnson-Glenberg et al., 2014). As VR HMDs have become cheaper and more robust, they grow more ubiquitous as tools for facilitating embodied training within virtual facsimiles of the real contexts. The instructor, however, has seen fewer advances in how they interact with the training material and the learner, typically observing a mirrored version of the learner's view of the scene from a nearby computer monitor. While studies on VR training do not traditionally consider the experience of the instructor with the simulation, research on collaboration in VR, reviewed here, offers insights that are useful to facilitating instructor workspace awareness in immersive training.

Each of the presented methods of instructor-learner interaction has different benefits and drawbacks. Within the VR HMD training configuration, there are various ways to deliver communication (computer-mediated compared to natural) between the instructor and the learner. For instance, while adding a second HMD for an instructor seems like an easy solution for providing full awareness access to the VE, research has shown that view congruency is still challenging to provide (Wong & Gutwin, 2014). It also cuts-off an instructor's perception of the physical space, which can be critical to completely understanding a learner's actions. Additionally, simultaneously accessing the VE with two HMDs is often not cost-effective. While asynchronous interaction allows the use of a single headset, it still means that one member of the group would be required to use a stationary 2D screen to access a 3D world and to engage in spatial reorientation to understand the other's actions. Alternatively, the instructor and learner may revisit the recorded experience to glean or give information, which means that while costs associated with procuring an additional HMD are cut, the time cost is potentially doubled. Projectors can be added to the physical set-up to enhance the outsider's understanding of the VE; however, space and money may not be sufficient to support these technologies. Instead, asymmetric VR which incorporates more typical technology such as computer monitors and keyboard/mouse set-ups or smartphones may be useful in mediating the interactions between the HMD-user and external users. By allowing the instructor to interact with the VE using such devices, HMD-users may be guided, aided, or tested during their embodied learning experience. Lastly, adaptive training is an expanding area of research in VR that can be used to provide custom training material and feedback, lessening the need for communication and workspace awareness on the part of the instructor.

Based on this review of the literature, the authors believe the best solution to the workspace awareness problem in HMD-based training is often a combination of existing methods. For example, by combining adaptive VR's automation of performance feedback with asymmetric VR's unique interfaces, instructors may be able to supplement feedback in real-time due to their simultaneous awareness of the learner's actions in both the virtual and physical worlds. Another potential solution may combine asynchronous VR use with asymmetric and adaptive VR as a way to review the actions of the learner in a robust way that is not currently possible. More work is needed to evaluate such hybrid approaches.

In addition to future research into combined categories of interactions, more research is needed in five specific directions: (1) Interaction tasks should be categorized and analyzed to better understand which are best supported by different interfaces. This work has begun in areas such as joint-manipulation of virtual objects (Grandi et al., 2019). However, more attention to observation and interaction tasks that move beyond artifact-interaction is needed. (2) The training transfer should be evaluated for training in adaptive systems, which either include or exclude a human instructor in-the-loop. By better establishing the impacts of instructor interaction on training outcomes, development can be directed appropriately. (3) The overall effectiveness of both asymmetric and adaptive systems for training should be evaluated. Relatedly, (4) there is an additional need for research on the behavioral impacts of asymmetric VR, especially due to its place in social VR interactions (Gugenheimer et al., 2017). Lastly, (5) future work should examine what aspects of the VR training experience should be automated to promote the highest efficiency of the HMD-based simulator training. As mentioned above, a combination of VR interaction approaches will likely be necessary to create the highest-quality VR training solutions.

This review aimed to survey the existing scope of research on VR use that is relevant to simulation training in immersive HMDs. Five themes of interaction styles were identified in the research to date and the literature's applicability to VR training in HMDs was discussed. This work will serve to embolden interservice, industry, and academic professionals interested in employing immersive VR and AR training to seek solutions to the challenges posed by this training-delivery method.

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