Firefighter Immersive Learning Environment (FILE): Literature Review

Final Report by:

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Foreword

Training is a critical part of the fire service. As new technological innovation applications (e.g., virtual reality, augmented reality, artificial intelligence, machine learning, robotics, etc.) emerge and are proven in other arenas, fire service training academies must investigate these to see their impact on the skills, safety, and wellness of firefighter trainees. This project seeks to leverage the immersive learning technologies that have proven to be beneficial in other high-risk occupations, such as military, law enforcement, health care, and identify the value of application of immersive learning for firefighter training.

The overall goal of this project is to identify, assess, and summarize the available and emerging technological tools, techniques, and innovations, to support the application of immersive learning environments in fire service training and address its impact on firefighter skills, health, and safety during training. The project objectives are:

- Describe the value of immersive learning on firefighter skills, and competency-based testing and evaluation.
- Establish baseline knowledge of Immersive Learning Environment that could be adapted to fire service training.
- Identify, prioritize the future needs and barriers of fire training academies to implement immersive learning.
- Communicate the needs of fire academies recognized and understood by others, especially technology innovators, and
- Create a firefighter immersive learning environment roadmap to provide guidance to fire training academies and others in support of implementing immersive learning.

The project is funded by a DHS FEMA Assistance to Firefighters Grant (AFG) FP&S Program to the Fire Protection Research Foundation (FPRF) and North American Fire Training Directors (NAFTD) as the principal project partners.

This two-year project consists of three primary components: (1) Literature review to develop baseline content and material that summarize the current landscape of immersive learning in fire service training and education; (2) Targeted focus group meetings with key types of NAFTD representative fire academies (e.g., large, small, community college based, etc.) to gain insight about the distinct training delivery systems of fire training academies; and (3) Stakeholder Summit to present, review, and evaluate the overall state of immersive learning technology in fire service training and develop a firefighter immersive learning environment (FILE) roadmap to provide guidance to fire training academies and others in support of future implementation of immersive learning.

This report is addressing the first deliverable of the three primary components of this project, i.e., literature review to develop baseline content and material that summarize the current landscape of immersive learning in fire service training and education. The subsequent additional deliverables from this overall project effort include a report summarizing the focus group meetings and a standalone document summarizing the firefighter immersive learning environment roadmap.

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About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

Keywords: training, immersive learning, education, professional qualifications, firefighting, fire service training, augmented reality, virtual reality, mixed reality, simulation, SWOT analysis.

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1. INTRODUCTION

Firefighters rely on strategic planning, motor skills, real-time decision-making, and other essential skills to succeed in their work. However, "real-world" firefighting situations are dangerous and difficult to control, making skill training and practice difficult. Immersive learning offers one solution toward addressing the need for realistic training.

Virtual reality and other forms of immersive learning have been used (and studied) in the context of fire service training for a long time: see Cater, 1994; Tate, Sibert & King, 1997; and Sims, 1995 for just a few early examples. Numerous tools are now commercially available that purport to provide effective training both specifically for firefighters and for general-purpose training. Many studies evaluate the benefits and limitations of immersive learning for training in general, and in fire service-adjacent contexts (including DeLorenzis et al., 2023 and Bakar, Sirotiak & Sharma, 2020). However, clear guidelines and criteria for what types of immersive training will be most valuable, effective, adaptable, and affordable for firefighters are lacking. Without a common understanding of the current terminology and technology in the immersive learning space, as well as the most pressing needs and concerns in the fire training space, consensus on which tools – if any – are necessary, compatible, or even helpful may be difficult. This report aims to provide background information on terms, applications, and useful considerations in the field of virtual reality – in conjunction with the known and (still) unknown needs of the fire service community – to establish a road map for future decision making.

The report explicitly addresses the following topics:

A. Definitions of major terms, including where disagreements exist;
B. The current landscape of virtual reality, including examples from both within and outside the firefighting space;
C. SWOT analysis of VR in firefighter training, including barriers to adoption;
D. Future needs analysis, indicating the process of identifying and integrating needs and solutions;
E. Gap analysis, suggesting what is most needed to fully address identified needs;
F. A knowledgebase of sources and further information (provided in a separate document).
Although immersive learning can be said to take many forms, the discussion in this document will focus primarily on methods associated with virtual reality and (to a lesser extent) augmented reality (see Figure 1). This is primarily because virtual reality occupies a “sweet spot” of relatively lower costs and greater benefits than many other forms of immersive technology, and is also among the most well-studied forms of immersive learning in general and in fire service contexts specifically. Section 2 provides more context on this focus.

The scope of this report does not include making specific recommendations as to what tools, methods and technologies should or should not be adopted by the NFPA or any other organization. The studies and examples presented here are intended to be illustrative rather than exhaustive; moreover, as technology evolves, there will almost certainly be more and different opportunities in immersive learning than we can currently forecast or describe. This report aims to provide a broad framework of understanding that will serve those evaluating the value of immersive learning for fire service training both now and in the future.

2. BACKGROUND

2.1. Terminology

The sheer volume of distinct and often conflicting academic, commercial, and layman attempts to define the concepts, vocabulary, and distinctions related to immersive learning, virtual reality (VR) and related fields demonstrate that defining terminology is neither a simple nor a neutral task. Decades of research and commercial efforts have produced definitions that vary for multiple reasons, including:

- **Lack of awareness** of established or pre-existing definitions and discussion;
- **Flag-planting** by those who want to set up their own viewpoints as “definitive”; and
- **New developments** that prompt re-evaluation; and
• **Self-serving distinctions**, where vendors and commercial efforts in particular will draw lines between concepts so as to exclude competitors’ products from certain definitions and emphasize their own as legitimate (e.g., “true VR”).

Bryson (1998) discussed these “definition wars” nearly twenty-five years ago, and as recently as 2022, work is still being produced that attempts to “define the field” (e.g., Rauschnabel et al., 2022). Despite the lack of agreement, however, some definitions can be set forth to create a shared sense of understanding. The following terms are defined as they are generally used in the context of this report, and common points of confusion or disagreement are noted.

Note that some existing definitions of virtual reality and associated concepts are technology-based, i.e., they define the concept by way of the technology used to produce or experience it. Bryson and others note the limits of this kind of definition, which fails to account for the replacement of one technology with another in service of the same result (e.g., consider film vs. digital technologies to produce motion pictures). Technology-based definitions also lack support for concepts and experience types which may not yet be supported by an existing technology. The definitions put forth in this report therefore avoid technology-based definitions.

### 2.1.1. Immersive Learning

The concept of immersive learning has both broad and narrow definitions. Dengel (2022) states that “Immersive learning can be defined as learning with artificial experiences that are perceived as non-mediated.” This suggests, in a fire service context, that immersive learning could take forms as different as artificial smoke and flames in a “burning” building, an emergency call from a trainer posing as someone in need of help, or a virtual reality session simulating equipment checks. More broadly, this could also include telepresence learning (e.g. video calls); projects like CAVE, with surround-screen immersion (see Cruz-Niera, 1993); and concepts like the “metaverse,” which is a widely discussed but still nebulous concept generally implying shared virtual spaces that could be used (in a training context) for distance learning, among other things.

Others consider immersive learning to be defined by the use of virtual reality and/or augmented reality – especially in commercial contexts. For instance, one vendor of virtual reality systems employs the following definition: “Immersive learning is an experiential training methodology that uses Virtual Reality (VR) to simulate real-world scenarios and train employees in a safe and engaging immersive training environment” (STRIVR, 2022).

As noted in the introduction, this report will focus primarily on virtual and (secondarily) augmented reality as they relate to immersive learning; thus, we will lean on the narrow definition. With that said, many of the considerations discussed here may be equally well applied to the “metaverse” or other immersive technologies/concepts that are not necessarily strictly virtual reality.
2.1.2. Virtual Reality

Virtual reality can be defined as “a medium composed of interactive computer simulations that sense the participant’s position and actions and replace or augment the feedback to one or more senses, giving the feeling of being mentally immersed or present in the simulation (a virtual world)” (Sherman & Craig 2018, 2002). Contemporary virtual reality implementations often (but not always) involve a head-mounted display, but as noted in section 2.2, such technology enables but does not define virtual reality.

The broader definition of virtual reality offered here encompasses concepts like 360° video, which some narrower definitions exclude (sometimes intentionally) because the only interactivity typically comes from looking around from a single vantage point. There are numerous instances of 360° video used in firefighting training.

2.1.3. Mixed Reality

Mixed reality refers to the combination of real-world and virtual elements, either by incorporating digital elements into the physical world (more commonly referred to as augmented reality) or by incorporating real-world elements (such as props) into a digital space (Pan et al., 2006).

2.1.4. Augmented Reality

Augmented reality is “a medium in which digital information is overlaid on the physical world that is in both spatial and temporal registration with the physical world and that is interactive in real time” (Craig 2013); or more simply, “a medium in which digital information overlays the physical world” (Huisinga 2017). Some consider augmented reality as a subset of virtual reality where real-world elements are included; others consider virtual reality as a special case of augmented reality where real-world elements are occluded; and still others consider the two completely separate. Notably, the Huisinga definition allows for some digital text overlays, e.g. speed projected on a dashboard, to count as AR; however, most would not consider simple text overlay to be AR. For a broad survey of AR, see Billinghurst (2015).

2.1.5. VR, AR, MR, XR

While virtual reality (VR), augmented reality (AR), and mixed reality (MR) have all been defined, there is disagreement on the distinctions between them, especially regarding AR and MR. Some don’t distinguish between those two concepts at all, and there is confusion in the field on how and when to differentiate between them.

“XR” is different from the other three abbreviations listed here because it can refer to two distinct concepts: eXtended Reality and “Anything Reality” (wherein “X” represents a variable that may be replaced with one of the -Reality types listed above). This latter definition, which we employ in this
report, is common in academic contexts, and Rauschnabel (2022) asserts that this is the generally accepted definition of XR.

2.1.6. Simulation

From an academic perspective, simulation refers to the underlying mathematical (or other) model that enforces the rules of the virtual world. Simulation can also broadly refer to engaging with an action in a way that reflects taking that action, rather than taking that action in actuality.

Firefighters may have context-specific meanings for the word “simulation,” but in this report the term may be used more broadly in line with the above definitions.

2.1.7. Locomotion

Navigation in VR consists of two components: Travel and Wayfinding. Locomotion is a means of travel in the virtual world and is typically meant as physically walking (or running), as opposed to having a button to simulate walking, etc.

2.1.8. Tracking (3DOF, 6DOF)

Tracking refers to how a system knows where the participant(s) are and where they are looking, etc. Technologically, there are numerous different ways to track participants, but overall, tracking methods can be categorized as “inside out” or “outside in.” In this context, it’s important to note that some systems track with three degrees of freedom (DOF) and some with six. Typical tracking for VR visual representation has six degrees of freedom: three orientation degrees and three location degrees of freedom, listed below. Generally speaking, if just 3DOF exists in a system they represent orientation.

The individual DOF types are:

ORIENTATION:

1. Yaw
2. Pitch
3. Roll

LOCATION:

1. X Location
2. Y Location
3. Z Location
3DOF systems may not be sufficient to fully train motor skills in the context of firefighting scenarios like running through a house. With only 3DOF, participants can’t (for instance) move behind objects to see different sides purely through physical motion. Degrees of freedom may be used as a differentiator, or even disqualifier, among vendors (with some potentially arguing that 3DOF systems (like typical 360° video) aren’t “real” VR).

3. CURRENT LANDSCAPE

3.1. Considerations

Immersive learning is currently being employed in training in myriad ways across numerous professions, including the fire service. Examples abound in medicine, manufacturing, construction, athletics, and the military, to name just a few. This report highlights several cases that have been studied or conducted academically; references to further reading can be found in the Knowledgebase, although the vast array of uses precludes the possibility of covering every instance.

Existing adoption of immersive learning can offer useful insights and lessons learned, but (as noted in the needs analysis below) discussion of whether or how to implement a new immersive training method should always be approached from the perspective of the specific need(s) at hand. There is no guarantee that the benefits of one implementation would directly transfer to any other scenario, or that there may not be drawbacks or opportunity costs that could prevent even a successful immersive solution from being the best option in some cases.

3.2. Current Use in Fire Service Training and Education

VR and AR have been used in fire service training for decades. Early efforts in the 1990s, like the Shadwell application (Tate et al., 1997) for firefighting on the USS Shadwell submarine, have evolved into the plethora of applications that are currently available today. VR has been used to rehearse fire missions, train on the use of firefighting equipment, and train decision making for firefighters. They have also been employed in teaching the public about firefighting, including the impact of how they drive around responding emergency vehicles.

Some firefighting applications have been fully 3D, tracked VR applications, and others have been simple (though effective) 360° video captures that allow a participant to “look around” from the perspective point of a 360° camera.

VR and AR are especially suitable for tasks that are 3D and time varying in nature, thus making them a natural match to the 3D, time varying tasks that firefighters encounter in their work. Examples include pump operation, fire truck driving, situational awareness, and wayfinding.
XR technology is evolving very rapidly and though currently primarily focused on sight and sound, other senses are being integrated at varying levels of detail and cost. There are technologies being developed for haptic and tactile feedback, smell, heat and cold, wind, etc. Hence, in the future, a much more robust environment will be available for firefighter training to a much higher degree of verisimilitude with their real-world tasks.

Two of the more well-established firefighting training systems currently in use by fire departments are listed below, although there are other examples of XR for firefighter training (and adjacent training, such as more general first responder training; see e.g. https://augmentedtrainingsystems.com/). Further reading, including a comprehensive review of XR in disaster management and VR for first responders (Khanal et al, 2022; Haskins et al., 2020) can be found in the Knowledgebase.

- FLAIM, an Australia-based VR training simulator for firefighters. Wearing a headset, trainees are immersed in real-life scenarios that can be too dangerous to reproduce in the real world; https://www.flaimsystems.com/
- RiVR: Fully interactive VR field laboratories enable the development of detailed virtual investigation scenarios. Which include full interior and exterior viewpoints of, for example, a burned-out warehouse or bedroom, allowing firefighters to train in an effective, safe and cost effective manner; https://youtu.be/kSeox2Zrk3c

In addition to systems actively in use, there are several academic evaluations of prototypes and early designs; unlike some fully commercial efforts, these academic efforts explain the tests used for measuring effectiveness and give insight into the theoretical underpinnings of successful (and unsuccessful) functions and features. One recent example is SAVE, a prototype AR headset intended to assist with training teams of search and rescue professionals (Luksas et al., 2022). See also: Spain et al., 2020; Shi et al., 2021; Grandi et al., 2021; Clifford et al., 2019; and Jeon et al., 2019.

3.3. Parallel Professions

Aviation Case Studies

Flight Simulators
Flying a plane is a high-stakes task requiring many hours of training and supported practice, similar to firefighting. Many commercial airlines, as well as military aviation units, have made use of VR flight simulators to provide training for pilots – for example, VRPilot (https://vrpilot.aero/). Virtual reality training is obviously safer and cheaper than logging real flight hours, but results compared to more traditional flight simulation can be varied. Oberhauser et al. describe a scenario in which pilots using VR training were able to complete training tasks successfully, but when compared to a control group were somewhat slower and less accurate with the VR system. Simulator sickness also posed a real threat to VR training efficacy as opposed to non-VR options, sometimes preventing trainees from completing all tasks (Oberhauser et al., 2018).
As technology improves, issues with latency, fidelity, and field of view (or the high costs that may prevent systems from obtaining the optimal settings) should continue to become less significant (Oberhauser et al., 2018; Engelbrecht et al., 2019). This technological advancement will enable VR flight simulators to overcome problems that can still plague them today – for instance, tradeoffs between latency and field of view that impede pilots from completing tasks quickly. However, VR training’s potential drawbacks in terms of developing pilot accuracy and speed need to be considered when determining the balance between VR, other kinds of simulation, and actual flight hours. The fire service should be similarly thoughtful about how and when to implement VR training for high-stakes tasks, considering when the potential of small hits to performance (in cases where such hits are likely) may be worth the savings in cost and improvements to safety over other training methods.

**AR for Maintenance and Repair**

Although the popular image of a firefighter involves rushing into a burning building, many life saving tasks firefighters need to complete are far more mundane. While immersive learning has been used in flight simulation for decades, it is increasingly being applied to training technicians on the care and keeping of equipment and tools as well. Researchers and companies are increasingly turning toward AR applications to assist with maintenance operations, either by enabling enhanced distance communication with experts (Safi, Chung & Pradhan, 2019), or by guiding technicians through specific processes to ensure correct completion (Yong & Sung, 2019). Eschen et al. (2018) point to four major use cases in aviation maintenance for AR applications to focus: virtual inspection, AR supported robot programming, ground test guidance, and process guidance. These applications will become increasingly important in aviation as the bulk of well-trained maintenance professionals begin to age into retirement, (Van Vooren, 2019).

Because identifying, diagnosing and properly addressing any equipment damage, malfunction, or wear is critical for planes and flight control systems, they provide an effective analogy for the fire service, for whom functioning gear, vehicles, and equipment can also mean life or death. AR applications may be able to enhance training on inspection, connection, proper operation, and on-the-job troubleshooting for firefighters, in addition to being a valuable tool for those whose main role is maintenance.

**American Football Case Study**

A VR application developed to train football players at the University of Illinois showcases iterative design based on user feedback and experience. The initial design used VR to simulate how players perform in actual, live practice: breaking the huddle, lining up, running the play, moving to position, engaging with an opposing player, and returning to the huddle. The goal of this initial design was complete realism in every aspect (e.g., player, field, stadium, fans, fan noise) in order to convince the player they are actually in a real game. When initial tests with players were conducted, however, the players stressed that other than the players and their positioning on the field, the other aspects of realism presented in the scene (e.g., fans, stadium, fan noise) were unnecessary and in some cases
distracting. Moreover, it was difficult to find sufficient indoor space to enable this end-to-end simulation in a way that was safe for the players, whose instincts were to move explosively even when the real boundaries of their space were more confining than the virtual boundaries. The conclusion from the first iteration was that a VR simulation should not be designed or expected to replace live practice.

This understanding led to a new design approach which focused solely on player positioning in response to an opposing team’s formation, a particular aspect of training for which the players needed many hours of repetition. Only the minimum required components that needed to be represented in VR for this training were rendered: realistic players and jersey numbers (for both offense and defense), proper football field markings, and a set of different “formations” for the opposing team which included player position, adjustments, and player pre-snap motions. The actual live play was never conducted; only the participant’s response to the opposing team formation before the live play. Notably, this setup helped address safety concerns as well, as the likelihood of unintended injury was reduced.

A takeaway for VR training in the firefighting space is that in some cases, modularized training, in which firefighters can practice singular choices, movements, and reactions in a minimally rendered environment, may be more valuable and/or feasible than training representing holistic, end-to-end chains of decisions and movements.

Archaeology Case Study

Archaeologists require training in not only motor activities (measuring, digging), but also planning and strategic activities (site choice, where to dig, etc.). An application created at the University of Illinois (Shackelford et al., 2018) incorporated VR to enable archaeology students to engage in simulated fieldwork without the high expense and potential risk of bringing students to active archaeological sites. In addition to VR, the application incorporated game elements to improve structure, involvement, and appeal. Participant responses suggested that the game elements (including exotic location and competitive tasks) added to the appeal of the simulation. Some participants noted that creating more narrative would have increased the appeal further: “I think just gave [sic] the cave a story, you know like this particular culture was in this cave, you are digging up this particular artifact for this reason. I think that would be helpful.”

Fire service has in common with archaeology a need for both physical and strategic training that can be expensive and difficult to provide. While game elements may not be appropriate for all aspects of firefighter training, they may be able to deploy competition and (as the archaeology researchers learned) narrative – to create compelling scenarios that develop strategic decisions, investigations, and planning, as well as physical aspects of firefighting.

4. APPLYING IMMERSIVE LEARNING TO FIRE SERVICE TRAINING

4.1. Strengths/Opportunities
For SWOT (strengths, weaknesses, opportunities, threats) analysis of virtual reality training for firefighters, this report draws heavily from “A SWOT Analysis of the Field of Virtual Reality for Firefighter Training” by Hendrik Engelbrecht, Robert W. Lindeman, and Simon Hoermann (2019) as well as the results of Focus Group discussions conducted by this project (see the FILE Focus Group Report for further details on group composition and results). Here we highlight some of the notable and compelling considerations for VR in the fire service space. Note that these considerations are not necessarily exclusive to VR; that is to say, VR, real-world training, and other methods may have overlapping SWOT characteristics (e.g. cost as a weakness) that would have to be weighed against each other on a case-by-case basis to determine relative value.

Strengths:

- **Cost-effectiveness.** Engelbrecht et al. point out that (at the time of publication) “obtaining a reusable structure for live fire training can easily cost up to one million US dollars” (p. 2), which does not take into account supplementary materials needed for each training or the fact that such a structure would not be suitable for a broad range of scenarios – e.g. fire truck driving, wildfire training. While initial costs for VR training are not insignificant, VR has advantages of accessibility, adaptability, and repeatability that substantially lower long-term costs.

- **All-hazards training.** VR can represent multiple training scenarios without requiring distinct equipment, vehicles and fuel, structures, etc. for each one as real-world training would. Multi-user options may allow for large-scale drills involving large threats and high numbers of responders that would not be feasible otherwise.

- **Safety.** The increased safety of virtual training methods is a strength that deserves special attention. Using real fire and smoke in training exposes firefighters to toxins and carcinogens and raises the likelihood of physical injuries. While these are risks firefighters face in the field, reducing these dangers outside of emergency situations is a meaningful benefit for both short- and long-term firefighter health and wellness.

- **Data recording.** Focus group participants referenced auto-documentation and instant performance review as strengths, while Engelbrecht et al. point out the potential value of intelligent training systems which can capitalize on that real-time review and adapt training accordingly.

- **Adaptable fidelity.** While higher fidelity is generally seen as a universal goal, being able to adapt fidelity to the needs of a task or system is a strength for VR. Often a schematic or map might be more beneficial than a highly rendered, detailed 3D computer graphics scene. It may also be beneficial to show a realistic house on fire, but then strip it down to a minimalist rendering to show the most important thing to focus on at that moment. Additionally, higher fidelity may either have no utility (fidelity of a particular scenario elements does not affect a participant’s experience) or negative impact (higher-fidelity leads to renderings that are so close to real they create distracting feelings of discomfort, especially when representing humans and animals – often referred to as the “uncanny valley”; Mori, MacDorman & Kageki, 2012). When higher fidelity is required, VR tools can integrate multiple computational techniques, e.g. computational fluid dynamics for smoke simulation.

- **Head-gear integration.** Because firefighters already wear headgear in their uniforms, unlike those in most professions, HMDs likely feel more familiar/comfortable than they might to those unused to
those situations. HMDs can also be integrated into, or made to look and feel like, on-the-job headgear. This increases the likelihood of participants accepting VR technology and decreases the likelihood of HMDs distracting or irritating the wearer.

Opportunities:

- **Technological and scientific progress.** Progress – which Engelbrecht et al. suggests could come in the form of better algorithms to show the movement of smoke, increased multi-sensory fidelity, more powerful multi-user integration, or a number of other avenues – is one of the strongest opportunities for VR. A look at the VR space ten, twenty, or thirty years ago showcases the changes that come over time with both better technology and better knowledge of how to put that technology to use.

- **Props** (Hinckley et al., 1994). A prop is a real-world object that is tracked and mapped to the VR graphical representation. For example, while in VR, the firefighter trainee might be holding an actual axe or nozzle that they can see in VR while they also feel the actual weight, momentum, etc. from the prop. Many VR applications just use generic hand controllers, but the opportunity to use props to great advantage exists.

- **Redirected walking** (Cmentowski et al., 2022). With redirected walking, participants walk in a circle but the display/experience shows them as walking in a straight line – convincing the participant that they are in fact walking in a straight line. This enables VR to take advantage of smaller spaces, while also prioritizing natural locomotion (without requiring specialized hardware, like omnidirectional treadmills).

- **Fun.** Focus groups highlighted multiple times that the potential for fun was a significant opportunity for VR. Training can be repetitive, especially when room for hesitation and error is small. The ability to add an element of fun – through game elements (competing against oneself, others, or an external threat), narrative, graphics, and even the “wow” factor of particular technological abilities – can potentially increase interest, engagement, and self-directed learning. These benefits may be even stronger over time, as younger generations are increasingly comfortable with digital gaming.

- **Jurisdiction specificity.** Because VR can be adapted to different scenarios and skills, different jurisdictions can take advantage of training that reflects the environment they operate in – for example, an urban fire department may focus on training for driving through traffic on virtual streets that match the layout of their city, while a West Coast department may spend time planning strategies for wildfires based on simulations situated in their environment.

4.2. Weaknesses/Threats

Weaknesses:

- **Technological shortcomings.** Engelbrecht et al. (2019) note that “the road to photo-realistic VR is still long,” highlighting latency, tracking, and field of view as aspects of VR that are “improving” but
still far from sufficient (p. 6). Focus group participants also noted that the lack of realism in both the visual field and the absence of advanced effects (like heat representation) is a current weakness in VR.

- **Lack of multi-user fidelity.** Firefighting requires team cooperation and communication. In many emergency situations, physical contact is a main pathway for this cooperation to occur (Engelbrecht et al., 2019). Without both technological and procedural support for multiple user interactions across different dimensions (including haptic/touch response), VR lacks support for a key dimension of firefighting. While some capacity exists for this in current technology, implementation significantly raises costs and complexity.

- **“Change is hard.”** Both Engelbrecht et al. (2019) and focus group participants (quoted) note that resistance to change, especially from older generations, can provide a significant barrier to adoption and also undermine the impact of training that is adopted. VR training requires instructors who are both knowledgeable about and amenable to the use of VR, which can entail practical obstacles.

- **False confidence.** Focus group participants raised the concern multiple times that mastering a skill or procedure within VR training can give trainees an inflated sense of their own preparedness for live situations. This may also contribute to a safety and exertion trade-off, where in VR participants could make “correct” choices with regards to safety despite the greater difficulty/exertion because the system rewards those choices, but are then not fully prepared for facing risks in the real world (because they have avoided those risks in training).

- **Adverse health effects.** Simulator or cyber sickness, which can stem from a mismatch between the participant’s physical motion and the motion displayed in a simulation (Wang et al., 2022), affects many people with nausea, headaches, and other physical symptoms that can impact or preclude their ability to benefit from VR training. Specific physical impacts like eye or neck strain from VR headsets, or injury from tripping/running into real-world obstacles that don’t show in the virtual environment, are possible as well. Long-term effects of frequent VR use have not been fully studied.

**Threats:**

- **No benefit over other options.** Training of any kind is only valuable insofar as it works – participants should gain knowledge, skills, familiarity, etc. While there are studies within the fire service and in other contexts that evaluate the effectiveness of VR training methods, more work is needed to be conclusive on where exactly learning benefits are stronger, weaker and perhaps nonexistent. Additionally, because multiple training types are in consideration for the fire service, VR training also needs to represent value over other options. Engelbrecht et al. note that in comparison with classroom instruction and live fire training, VR “should occupy the gap…where cost (or complexity of administration) and utility meet” (2019, p. 9). If VR systems cannot situate themselves effectively in the training space, they may not ultimately yield enough benefit to justify implementation over other options.

- **Over-gamification.** The promise of adding game elements to improve engagement/enjoyment in training can lead to an undesired secondary effect, wherein participants may then be less likely to engage when those elements are removed; for example, thoroughly completing a checklist to earn
points in training, but skipping items in the real world when there is no extrinsic reward for thoroughness (Engelbrecht et al, 2019). Focus groups also raised the concern that gamification may attract vendors from the gaming industry, who may ultimately crowd out other options with training that prioritizes game elements over training needs.

- **Cost.** While cost to entry for VR is much lower now than in the past, and may compare favorably to some other training options, costs associated with an immersive solution could still pose a threat to adoption. Maintenance and/or subscription costs can also present a possible hurdle to continued use. Implementing technology-based solutions requires either internal or external expertise to install, launch, and support systems, which can incur additional costs in either salaries or vendor support. Federal grant opportunities for fire service VR training are currently limited and may be considered lower priority than funding requests for equipment or personnel.

- **NFPA standards.** It is currently unclear whether and how virtual reality (or other immersive learning techniques) can be used in the evaluation of NFPA standards in testing. Further clarity would be needed to help those considering adoption of these methods understand the value of the tools in question.

### 4.2.1. Barriers

The biggest barriers to adoption of XR immersive training systems are knowledge, cost, technology, and in some cases, lack of knowledge surrounding, or lack of appetite for, new training methods. These factors will vary on a vendor, department, and person basis but would need to be taken into account when making policy and recommendations.

Another current barrier is the lack of a very specific task analysis / training needs analysis that can be mapped into immersive training scenarios. A distinct but collaborative needs analysis is essential for both the training and the system itself, involving input from both fire service experts and those in charge of curriculum and system development. For example, a training analysis would include the need for the firefighter to perform task X in Y time, or navigate a building with fewer than X wrong turns. (While the NFPA Job Performance Requirements mentioned below in section 4.3 likely provide a good start for this, they may need additional detail or clarified scope in order to map clearly with system design.) A system requirement might be that the system must be portable and able to be deployed by a typical firefighter trainer in a typical training room. It could say that it needs to be able to allow the firefighter to run infinitely in any direction, or to climb stairs. It could be that a requirement is that the firefighter use a real world prop (like a real firehose) for a certain task. These details, worked out in consideration of both training and system perspectives, are critical to an effective outcome.

### 4.3. Identify Future Needs of Fire Service Training

Identifying fire service training needs and translating those needs into cohesive requirements and training design will involve the consideration of multiple factors, including technological requirements, cost, adaptability, etc. The following is a loose outline of the recommended process:
1) The NFPA Job Performance Requirements (JPRs) provide a starting point for a detailed needs analysis. A needs analysis must specify the skills and concepts that firefighters need to know, as well as the performance metrics that should be evaluated for these skills/concepts.

2) Mapping of skills and concepts into a matrix that can then be used to determine what method / tool / technology is best utilized for TEACHING that skill or concept, and likewise what method / tool / technology is best utilized for PRACTICING that skill or concept.

3) Those that are suitable for VR or AR (if any) can be mapped into a needs requirement for the software to be developed or procured to support that element of the training.

4) Determination of the instructor’s role and the software’s role in teaching and practicing each skill, including the training delivery system and training authoring system (e.g., methodology for instructors to generate their own scenarios and exercises from scratch or from a menu of options).

5) Determination of what level of sophistication is required for the underlying simulation for each task. For example, some tasks may simply require a 360° video, whereas others might require a full 3D-model with high-fidelity simulation, some kind of treadmill, heat and haptic transducers, etc. Most tasks will likely require support for multi-person environments.

6) Integrating cost into the matrix to determine how each necessary and desired capability affects cost, and which needs may be more cost-effectively addressed by VR vs. non-VR methods.

Because this process is involved and requires input and consideration from multiple perspectives, it may make sense to start with a “proof of concept,” looking at a small subset of agreed-upon JPRs and the skills they lay out for firefighters. Going through the process can help identify knowledge gaps and potential roadblocks, and help determine whether a more comprehensive analysis of all (or even a larger subset) of JPRs is worthwhile.

4.4. Gap Analysis

Some of the gaps between the current situation and potential new adoption of XR training for the fire service are within NFPA control, while others require input and advancement from others. High-priority gaps include:

Task/training needs analysis. As described above, which tasks – e.g., from those among the NFPA JPRs – will be best represented/improved with VR support? Which methods, tools, and technologies are best suited to supporting those tasks?

VR / AR training expertise. There is a dearth of experts who can develop research-based VR / AR training, incorporating and relying on context-specific guidelines. There is also a gap in the ability to evaluate the expertise that has been invested in currently available training: in most cases, the current VR and AR applications for firefighting training and education have not been studied and tested fully. The field is currently overly reliant on vendor claims as to the efficacy of the systems they are trying to sell.

General-purpose software. Not enough training software exists that is suited for general-purpose use, that can be adopted or adapted by the fire service. Many fire service tasks (e.g., driving, determining the
best path to an exit) could be present in training that is not specific to the fire service, but could benefit it nevertheless.

**Training deployment expertise.** For existing software, there is often a lack of expertise as regards the best practices for deployment. Instructors need to be trained before they can be trained in turn. Assessing when specific portions of a training system will be most useful, and to whom, is not always simple.

**Underlying simulations.** There need to be good, realtime underlying fire models with realistic evolution and smoke, based on the firefighters’ interactions with them, the weather conditions in the simulation, etc. Currently, supercomputers are used for these kinds of simulations that still might or might not be fully what they need to provide realistic training. Decisions will need to be made regarding what kinds of details are necessary and sufficient – e.g., to what extent does fire need to behave realistically? Does smoke need to burn the participants’ eyes? How realistic do the consequences need to be in response to mistakes or circumstances outside firefighter control?

**3D models.** While there are many 3D models of environments and structures, more – and more specific – options are needed. Training instructors need to be able to quickly construct scenarios of interest using particular models. For instance, they might need models of specific buildings in a certain block in Chicago, or models of specific kinds of railroad cars with certain kinds of contents. Having these to hand would allow for the training to be adaptable and flexible to representing different kinds of hazards. Most of these specific models do not yet exist, which means some kinds of training are rendered either meaningfully imprecise (and potentially distracting), or not at all.

**Special-purpose hardware.** There is a lack of hardware created specifically for firefighting tasks, which may be needed to optimize simulation of particular conditions.

**Performance data analysis tools.** There need to be tools for analyzing the performance data that comes from the training system, to measure effectiveness and highlight areas for improvement. The goals for training may come from the NFPA, but those goals need to be integrated with system feedback. For example, if a firefighter needs to be able to identify faulty wiring – what training performance data represents the line where they are or are not considered to possess that skill? What speed, accuracy, and detail are needed?

### 4.5. XR: Past, Present, Future

As technology continues to develop, both the possibilities and complexities involved in XR will evolve. Haptic and other non-audiovisual technologies offer one avenue for change; another is repurposing some of the tools (especially AR) developed for training into tools that are used on the job itself. For example, a tool might display to a firefighter in real time a checklist based on the current conditions, data regarding temperature or oxygen level, or predictions of fire movement. Due to the higher stakes involved in real-life job situations, the requirements for these tools would be stricter than for training.
Security, resilience, error-proofing, and integration with non-XR tools would take on even more importance.

4.6. Conclusion and Recommendations

In most cases, immersive learning is not currently suited for nor recommended for replacing live training. Immersive learning should optimize across the parameters of cost (less expensive than e.g. live fire training) and impact (more effective and engaging than e.g. classroom instruction, training videos). Where immersive learning can occupy that optimal space on the training continuum, **immersive learning environments are recommended as one of the most important parts of a blended learning environment**.

Prior efforts in XR training have shown that attempting to fully replicate physical experiences in every detail as a stand-in for live situations is not an ideal strategy, especially with the limitations of current technology. Existing instructional methods are not recommended to be entirely replaced by immersive learning. Rather, the realism brought forth with immersive solutions is deployed to enhance retention, speed to decision, and accuracy of choices.

Virtual and augmented reality are suggested as especially useful for motor skill development, rote drilling and memory retention by presenting targeted scenarios to teach and reinforce specific skills, habits, and processes. XR training can enhance these skills and develop muscle memory (physically or figuratively) that kicks in when the participant encounters the training scenario in the real world. Game elements in training can also enable engaging training and broaden impact to strategic thinking, cooperation, and multi-user coordination.

To employ XR training methods for firefighters most effectively, training design should seek to zero in on particular aspects of training in which firefighters can practice their responses, movements, and reactions related to live fire training and on-site scenarios. Once identified, the next step is to determine the minimum required components that need to be represented in 3D/VR for successful training. The end goal is that firefighters using such a system would be trained in proper response to a variety of scenarios in such a way as to become second nature and without hesitation when the firefighter encounters the scenarios in the real world.

5. PROJECT TEAM

David Bock
David Bock is a Lead Visualization Programmer and VR developer with the National Center for Supercomputing Applications where he is involved with the research and development of rendering systems for visualizing scientific data. His system has been used to visualize data from a variety of computational simulations including density currents, hurricanes, binary neutron stars, tornado-producing thunderstorms, wind-farm simulations, climate models, and galaxy clusters. His work has been featured in the book Visual Computing, publications including Computer Graphics World,
Physics World, and Astronomy Magazine, and presentations and papers at Supercomputing, SIGGRAPH, XSEDE, and PEARC conferences. Bock has designed and implemented several virtual reality training applications in various disciplines including college football, flight training, and fire training. Bock is also Professor at Parkland College in Champaign, Illinois in programming, 3D computer animation, and gaming. Bock received his M.F.A. in Graphic Design and his Master’s degree in Art Education both from the University of Illinois at Urbana-Champaign. He received his Bachelor's degree in Electrical Engineering from the University of Southern Illinois in Carbondale, Illinois.

Dr. Alan B. Craig
Dr. Alan B. Craig is an independent consultant in Virtual Reality, Augmented Reality, Visualization, and High Performance Computing. Prior to this role, he contributed much to these fields during his thirty-year career at the University of Illinois at Urbana-Champaign (UIUC) as a Research Scientist at the National Center for Supercomputing Applications (NCSA) and as Senior Associate Director for Human-Computer Interaction at the Institute for Computing in Humanities, Arts, and Social Science (I-CHASS). Among his other consulting roles, he is currently engaged with the Extreme Science and Engineering Discovery Environment (XSEDE).

Dr. Craig has been called upon to speak as an expert in VR and AR at countless worldwide events and continues to speak at various venues. He has taught classes related to VR and AR online as well as onsite at universities, companies, and high school campuses. Dr. Craig has worked with government and industry entities regarding VR and AR applications. He has been interviewed by numerous publications, television, and news outlets.

In addition to Understanding Virtual Reality (with William R. Sherman) he also authored Developing Virtual Reality Applications (with William R. Sherman and Jeffrey D. Will) and Understanding Augmented Reality. Additionally, he has written multiple book chapters and articles. He has developed many virtual reality and augmented reality applications in content areas ranging from archaeology to zoology. He also teaches and advises on related topics. His primary focus has been on the use of virtual reality and augmented reality in educational applications and his work centers on the continuum between the physical and the digital.

He holds three patents.

Brendan McGinty
Brendan McGinty has designed and developed technology- and media-based training in nuclear operations, peace officer driver safety, environmental protection, insurance claims, and other topics for the U.S. Dept. of Energy, State of California, Environmental Protection Agency, State Farm, and many other public and private organizations. As an instructional designer, he and his teams have focused on instructionally effective content, stimulating delivery that leads to improved retention, intuitive user interfaces, and tracking of training effectiveness. McGinty leads the Industry Program Office for the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign and serves as Executive Director for the Center for Digital Agriculture and Director of Industry for the Center for Artificial Intelligence Innovation. He received his Bachelor’s degree in Liberal Arts & Sciences from the University of Illinois at Urbana-Champaign.
6. REFERENCES


