Advancing Electrical Grid Operator Training through eXtended Reality (XR) Technology

Charis Horner, Diana Perera, Dr. Melynda Hoover
Design Interactive Inc.
Orlando, FL
Charis.Horner@designinteractive.net,
Diana.Perera@designinteractive.net,
Meylnda.Hoover@designinteractive.net

Stacey Sanchez
Raytheon Intelligence & Space
Orlando, FL
Stacey.Munoz@yahoo.com

ABSTRACT

Energy grids have rapidly evolved in recent years, becoming increasingly complex as the Department of Energy (DOE) introduces scores of innovative technology and systems. The DOE has made significant investments in applied scientific research and the development of new clean energy technologies (DOE, 2016). The aim is to ensure America's critical energy infrastructure can quickly recover from disruptions and support the ever-increasing reliance on electricity. Though major strides in advanced technologies have been made in support of energy generation, transmission, and distribution, little progress has been made on innovative ways to train new operators who need to utilize and maintain these new technologies. Augmented, virtual, and mixed reality – known collectively as eXtended Reality (XR) – can provide a significant impact on training for electrical grid operators. These technologies allow for immersive, embodied training that can yield more effective knowledge and skill acquisition, provide substantial learning gains, and reduce time to proficiency. The introduction of XR technology to training can result in enhanced learning experience and increased trainee motivation and engagement. Using XR technologies, new grid operators can receive hands-on training with real-time feedback in an immersive, contextually rich training environment that replicates real operational stressors and workload demands required of electrical grid operators. This paper details existing grid worker training methodologies and discusses relevant XR training augmentations to meet training needs more acutely.

ABOUT THE AUTHORS

Charis Horner is a Product Engineer III on the XR Ecosystems Team at Design Interactive, Inc (DI). Her experience surrounds shepherding the creation of innovative software solutions and her current work centers around delivery of XR training and operational support solutions. She serves as project manager of multiple $1M+ efforts, primarily focused on customizing existing solution platforms to meet customer needs. She holds a Bachelor of Science (B.S.) in Industrial Engineering from the University of Central Florida with a minor in Engineering Leadership.

Diana Perera is a Research Associate I on the XR Ecosystems Team at DI. Her experience includes conducting human factors research and end-user evaluations of interactive systems and product concepts. She specializes in needs analysis, end-user research, and data analytics. She holds a B.S. in Human Factors Psychology and Master of Science (M.S.) in Human Factors from Embry-Riddle Aeronautical University.

Dr. Melynda Hoover is a Portfolio Manager at DI and has over 8 years of expertise studying Human-Computer Interaction and XR systems. Her research has focused on training applications of XR technology as well as collaboration, adaptation, and locomotion in XR. Dr. Hoover earned her Ph.D. in Human Computer Interaction from Iowa State University of Science and Technology. While at Iowa State, she conducted laboratory research at the Virtual Reality Applications Center, where she studied the efficacy of presenting in-situ training material to Boeing factory workers using the Microsoft HoloLens.

Stacey Sánchez is the Principal Human Factors Engineer at Raytheon Intelligence and Space. She has 13 years of experience relating to pilot and maintainer vehicle interface design and ground and flight testing. Her experience includes serving as the Human Factors Subject Matter Expert on the Qualification Assurance Board at Sikorsky Aircraft Corporation. Throughout her career, she has led several human factors flight test programs and served as the pilot vehicle interface design lead on multiple platforms. Stacey earned her M.S. in Aeronautical Science specializing in Human Factors in Aviation Systems from Embry Riddle Aeronautical University.

Advancing Electrical Grid Operator Training through eXtended Reality (XR) Technology

Charis Horner, Diana Perera, Dr. Melynda Hoover
Design Interactive Inc.
Orlando, FL
Charis.Horner@designinteractive.net, Diana.Perera@ designinteractive.net, Meylnda.Hoover@designinteractive.net

Stacey Sanchez
Raytheon Intelligence & Space
Orlando, FL
Stacey.Munoz@yahoo.com

INTRODUCTION

As reliance on technology increases, demand for electrical energy subsequently increases, introducing challenges to energy production and distribution. In recent years, the Department of Energy (DoE) has invested in scientific research to modernize the energy grid in an effort to make America's electric infrastructure more reliable, efficient, ecological, and secure (Butt, et al., 2021; DOE, 2016). Increasing grid resilience through modernization has the potential to reduce the frequency and duration of power outages and restore power quickly when these outages do occur (DOE, 2020). Though major strides have been made in advancing technologies to support energy generation, transmission, and distribution, little progress has been made on innovative ways to train new operators who need to utilize and maintain these modern technologies. This is a critical gap because if grid operators are not well trained on new, complex grid systems, critical mistakes could occur resulting in unplanned outages with catastrophic effects on health and safety.

Today's grid operators must also manage high-stress emergency events, but difficulty exists in training for these eventualities, as they occur infrequently and are difficult to simulate. Exacerbating these difficulties, grid operators are retiring in unprecedented numbers, taking years of knowledge and skills with them (Moen, et al., 2016). Experienced operators have spent decades learning these systems and over time have developed competencies needed to recognize faults while maintaining situational awareness of causal relationships and second-order effects in high-stress environments. Due to the increasing complexity of the grid and mass exodus of experienced operators, new grid operators must have the ability to acquire these skills more quickly than ever before and effectively apply these skills in high-stress situations. Therefore, there is a need for training augmentations to meet the needs of new operators and rapidly prepare them for complex decision making and performance under stress.

Augmented, virtual, and mixed reality – known collectively as eXtended Reality (XR) – can be used to solve some of today's challenges in the electrical grid training field. XR technologies allow for immersive, embodied training that can yield more effective knowledge and skill acquisition, provide substantial learning gains, and reduce time to proficiency over traditional training methods (Stanney et al., 2021). XR can enhance the learning experience and increase trainee motivation and engagement. Using XR technologies, new grid operators can receive hands-on training with real-time feedback in an immersive, contextually rich training environment that replicates operational stressors and workload demands required of electrical grid operators. XR training can assist with effective training transfer, potentially resulting in accelerated progression of expertise and improved performance of grid operators. The introduction of XR training can also assist with the minimization of training cost, as XR can replace or customize high-fidelity simulators.

The current paper details existing grid worker training methodologies and discusses relevant XR training augmentations to meet training needs more acutely. This begins with a description and evaluation of the current grid operator training process for control room certification, obtained via semi-structured interviews with grid operators. The evaluation provides insight into the existing state of grid operator training and its limitations. A discussion of the application of XR modalities and their suitability for grid worker training follows. Finally, the analyses of grid worker training and XR technologies are merged in a case study applying XR training to switching operations. In the conclusions section, the authors discuss future recommendations for implementing XR training in grid operations.

CURRENT ELECTRICAL GRID TRAINING PROGRAM

To set a foundation of the current training program for grid operators, subject matter experts (SMEs) from FirstEnergy and the Electrical Power Research Institute (EPRI) were interviewed and documentation surrounding their program explored. Existing training for new grid operators consists of an orientation and four phases lasting twelve to eighteen months, including both instructor-led and online components. Orientation and initial training occur during the first two weeks of the program, where topics include history of the grid, electrical theory, and control room observation.

Phase one lasts three to five months and focuses on trainees obtaining their Pennsylvania, New Jersey, and Maryland (PJM) and North American Electric Reliability Corporation (NERC) certifications (PJM, 2022; NERC, 2022). Courses in this phase cover the basics of power systems, power station energy production, power transport through transmission and distribution lines. They also cover information on circuit breakers and substation entry.

Phase two begins at the seven- or eight-month mark and consists of in-depth instructor led courses. In this phase, trainees learn about Energy Management System (EMS), the automated system which collects field energy measurement data and shows it to operators through charts, online monitoring tools, and energy quality analyzers (Zhou et al., 2018). Topics in human factors, communication, switching, tagging, safety, and equipment are also covered. Here, trainees also begin to sit in a simulator and practice switching and learn what to do during the loss of the EMS.

Phase three begins at the nine- to ten-month mark and consists of instructor led courses that provide training on more advanced switching (properly writing sequences that deenergize equipment) and tagging (determining what equipment can be energized). Trainees also begin practicing with different tools used in the control room. This phase also includes job shadowing of an experienced grid operator within the control room.

Phase four lasts five to six months and includes on-the-job training (OJT). During OJT, trainees have qualification cards they must complete to show they are competent in various skill areas. Once the qualification cards are complete, trainees must acquire recommendations from the crew and the manager stating they are ready for the final board exam.

During the final exam, the trainee must write their own switching, check switching, and conduct switching within their simulator. During the simulator portion, trainers roleplay as people in the field, causing equipment to fail to see how the trainee will react. Finally, there is an oral review board that focuses on electrical theory and other topics. Once they successfully pass this exam, the trainees can work in the control room as grid operators.

Training Limitations

Current grid worker training methodologies have limitations, such as high levels of stress not accounted for during training, lack of available tests for soft skills that are crucial in the operational environment, and unnecessary strain placed on experts during the on-the-job training for novices. Many other factors can also influence training effectiveness, such as environment, training style, job-related factors, attributes of trainees, and support from peers (Punia et al., 2013). As learned from interviews with SMEs, the environment where trainees learn differs greatly from the eventual working environment of the control room. This mismatch between learning environment and work environment can make it more difficult to transfer knowledge. Training is primarily classroom based and involves trainees utilizing a computer for online components of their training, but in the control room, operator desks typically utilize four or more monitors. Using additional monitors to gather information can result in more cognitive workload than trainees are exposed to in the training environment. A need thus exists to ***match the training environment more closely to the real environment***.

The operational environment also introduces high levels of stress not accounted for in current training methodologies. Grid operators have a higher level of responsibility within the control room and, in turn, a higher potential for stress on the job. They are responsible for anything that may happen on the field, even if they did not cause an incident. They must follow a strict set of procedures and flowcharts when dealing with a situation, and if it is not followed fully, they will have to explain exactly why not. This can cause a higher amount of cognitive and sensory workload on grid operators as they must ensure they are not missing any steps of the procedure. Trainees, on the other hand, do not experience the same stressors during training. Training is a safe environment for them to learn crucial knowledge, skills, and abilities, but does not always provide the best opportunities to apply what they learned. By not having a way for trainees to experience training environments akin to the stress of the real control room, they may have a harder time handling situations such as unplanned outages. Therefore, grid operator training needs a way to ***introduce relevant, high-fidelity stressors*** to prepare trainees for the control room.

Trainees may pass through the entire eighteen-month training program and have all the technical information to complete the job but be lacking soft skills important to being a successful grid operator, such as calmness under pressure during an unplanned hurricane outage. Affective, or “soft”, skills, such as calm temperament, multitasking, communication, and level-headedness when encountering stress are crucial to success in the control room. These skills, however, are difficult to test and measure in training environments. It may be simple to periodically evaluate trainees and ensure that they are comprehending and mastering technical learning objectives but ensuring trainees can apply this knowledge to the control room while displaying human interaction soft skills remains complex. There is, therefore, a necessity to ***improve and evaluate trainee affective skills during training***.

In the final phase of the novice training, trainees must conduct OJT while shadowing expert grid operators. During this training phase, a heavy burden is placed upon experts to complete their own job tasks while assisting trainees in real-time. This can divide the expert operator’s attention, potentially causing them to miss crucial information. This training practice also results in learning disparities for trainees because expert operators may use different training methods. Furthermore, expert operators typically do not have previous experience with teaching, making them ill-prepared for training responsibilities. The final need, therefore, is ***to lessen the strain on experts during the final phase of OJT while ensuring trainees still have on the job experience***.

EXTENDED REALITY (XR) FOR TRAINING

XR was evaluated as an enabling technology to potentially overcome the limitations of current grid operator training. In recent years, applications of XR have seen proliferation across industries for training (Billinghurst et al., 2015; Chatzopoulos et al., 2017). Traditional definitions of XR span the virtuality continuum from augmented reality (AR) to virtual reality (VR), and to the collective mixed reality (MR; Milgram & Krishno, 1994). These technologies allow for immersive, embodied training that can yield more effective knowledge and skill acquisition, provide substantial learning gains, and reduce time to proficiency (Stanney et al., 2021). Intentionally designed XR environments have the capability to digitally represent or augment the trainee’s actual environment and introduce high fidelity stressors to improve real-world context of training environments (Stanney et al., 2021). Furthermore, stressors can be applied to the virtual environment adaptively to help trainees learn to acclimate and deal with stressful conditions (Ćosić et al., 2011). Additionally, XR can reduce strain on instructors and experienced grid operators to provide guidance to novices or trainees by digitally replicating the contextualized guidance often provided via these individuals (Claypoole, et al., 2020a). Similar capabilities and benefits are, therefore, possible when applying XR to the electrical grid training space. Before determining the proper application of XR to grid training, prudence demands a consideration of the benefits and drawbacks of each XR modality as applied to grid operator training.

On the lower end of the virtuality continuum, AR enables the user’s real environment to be “augmented” with digital, computer-generated assets and overlays, which may or may not be interactable (Riley et al., 2020). Within the grid training space, this may involve situating a trainee in the control room or commensurate environment with visual and/or physical access to the applications they will use on the job, then overlaying real-time digital instruction and feedback onto their actual systems. Through AR, high levels of embodiment, immersion, and contextualization can be achieved to enhance learning. In many applications, the ability for the AR user to continue to see their physical environment allows for heightened contextualization, as instructive digital augmentations can overlay on their workspace, minimizing friction in the transfer of training understanding to real world application. However, modern AR hardware and spatialization technology have yet to reach high levels of accuracy when affixing digital information to the real environment, suggesting that AR may not be suited to tasks that require extreme precision (Riley et al., 2020).

On the other end of the virtuality continuum, VR allows the trainee to be fully immersed in a digital environment (Kaplan et al., 2020). Applying VR to grid training may involve the trainee being physically located in a classroom, then donning a head mounted display (HMD) that shows a digital rendering of the control room, including visual and auditory cues present in the true work environment. In this way, VR can allow a trainee to experience a high-fidelity and compelling rendering of an inaccessible environment. The use of VR for training has also been linked to the improvement in the understanding of complex concepts (Checa et al., 2020). However, creation of VR environments remains a limiting factor, as development timelines are often extensive to fully recreate a digital scene of the real world. This can be a potential barrier to adoption and customization of the technology to multiple use cases, as extensive costs may make the technology prohibitively expensive (Viglialoro et al, 2021).

Mixed Reality can be understood as the midpoint of the virtuality continuum between AR and VR. MR blends components of a trainee's physical environment with their actual environment and facilitates interaction between the two (Kaplan et al., 2020). MR can blend digital and physical visual, auditory, and haptic components to create a training experience tailored to the use case. For example, in the grid training space, users can be situated within the physical operating environment with digital content integrated into their environment, while being prompted to tactually interact with both the physical environment and digital content. MR by nature is highly customizable, so this modality provides instructional designers ability to tailor critical sensory cues to activate recall and enhance learning. The customizable nature of MR, however, also can require extensive research, development, and iteration to achieve suitability to a training application. Similar to VR, this can become cost prohibitive as each application may need to be extensively tailored to each use case.

For the grid operator training space, AR is recommended as the modality of choice. Within grid operations, trainees typically have access to their operational environment and must learn to interact with their physical systems without requiring fine psychomotor precision. Primarily, the skills trainees need to learn are gross motor skills (locating and accessing the right system in the right order at the right time) and cognitive processing (identifying, remembering, and responding to critical cues with cognitive decision making). AR has been found to be highly suitable to tasks with these characteristics and surpasses the ability of VR in skill acquisition (Riley et al., 2020; Khademi, et al., 2013). AR can also be highly customizable with low levels of development effort, ensuring proper scaffolding of scenarios to trainee proficiency while reducing cost. Appropriate scaffolding of XR training to a trainee's proficiency level is a critical component of ensuring learning progression and previous research dictates principles of implementation (Stanney et al., 2021). As such, a solution applying appropriately scaffolded AR training within grid operator training is subsequently discussed.

OVERCOMING GRID TRAINING LIMITATIONS USING XR

In pursuit of providing the benefits of an adaptive AR training environment to grid operators, an expert-informed, adaptive AR training tool called AMPed (Advanced Master Pedagogy for Electric-power Domain) was conceptualized. AMPed was designed for electric grid operators in need of innovative training and incorporates expert tips and tricks into proficiency-based training scenarios with tailored feedback to accelerate skill acquisition. To heighten the benefit of an AR application in the grid operator space, AMPed focuses on appropriate scaffolding to proficiency level (see Hatfield et al., 2019; Claypoole et al., 2020b; Claypoole et al., 2021). AMPed aims to provide a next-generation immersive training platform that incorporates expert knowledge and consideration of trainee proficiency into a user-centric solution. AMPed closes each limitation within current training approaches, as it is designed to 1) lessen strain on experts during OJT, 2) more closely match the training environment to the real environment, 3) introduce relevant, high-fidelity stressors, and 4) improve and evaluate trainee soft skills during training.

AMPed first captures expertise from experienced grid operators. Using a scientifically grounded, AR-facilitated knowledge elicitation approach, expert tacit knowledge which may be lost as experienced operators retire is elicited and preserved (see Claypoole, et al., 2020a for details on approach). By capturing this tacit knowledge, AMPed ensures a library of information that can train across all dimensions of understanding. ***This reduces the burden on experts during trainee OJT***, as experts can give their knowledge once, and have it repeatedly shared in a digital format directly to the trainee.

AMPed facilitates the creation of proficiency-based AR training by coupling captured expertise with existing training documentation. AMPed is also designed to repeat the success of previous efforts which transferred domain knowledge and skill acquisition across the training continuum by applying an XR-based cognitive scaffolding framework to the creation of AR training (see Claypoole et al., 2020b; Claypoole et al., 2021). Scenarios within AMPed are designed with real-time corrective feedback appropriate to the trainee's proficiency level. For example, a novice is given immediate, elaborative feedback for both correct and incorrect behavior to reinforce understanding, while a competent trainee is only provided feedback upon making an error as a method of correction. ***As appropriate by proficiency level, AMPed also supports introduction of relevant, high-fidelity stressors*** (e.g., timer countdowns, distracting audio cues) to prepare trainees for the control room. This aims to enable trainees to practice dealing with stress and distractions without compromising safety.

AMPed's training scenarios modernize the process of acquiring cognitive and psychomotor skills while providing a new mechanism to train and evaluate affective skills. Cognitive exercises encourage trainees to practice processing information from their systems and make decisions regarding when, how, and where to conduct operations, modernizing current classroom-based approaches. For psychomotor exercises, trainees have the access to their physical systems by interacting with monitors displaying information relevant to their job. Affective exercises situate trainees in context with real or virtual actors to simulate interpersonal experiences affording training and evaluation of soft skills such as empathy, temperament, and communication.

AMPed's training is designed to match the training environment more closely to the real environment. By overlaying digital elements (realistic scenarios, instruction, visual guideposts to critical information) on physical monitors (currently used in simulation environments), AMPed supports situated learning, allowing for the presentation of realistic operational conditions during training. The development of training scenarios within this solution is accelerated by the usage of a modular, open architecture that supports the interchange of core components, including models and end-user hardware, minimizing reconfiguration for each scenario and environment. In this way, training scenarios within AMPed can be rapidly generated with minimal development time. AMPed implementation is anticipated to lead to high levels of training transfer, maintained proficiency, and deterrence of skill decay, resulting in effective transfer of training and elevated performance under conditions of high workload and stress.

CASE STUDY

This section presents a case study that will contextualize the AMPed training concept. The authors gained access to specific use case information through direct partnership with SMEs (i.e., training supervisors, trainers, and transmission instructors). In this section, grid operator tasks and subtasks are evaluated through discussion of SME interviews, questionnaires, and technical documentation review. Through an evaluation of the criticality and frequency of these tasks, the selection of the writing switching use case is justified. A task analysis is then presented to explain the relevant training requirements for the selected use case. Finally, the implementation of AMPed to this use case is discussed, evaluating how well the conceptualized solution can meet the needs of the specific use case.

Task Selection

Through SME collaboration, it was suggested to focus on outage management tasks for initial implementation. Outage management includes coordinating planned outages, (i.e., field personnel, transmission operators, and stakeholders work ahead of time to plan for power loss for scheduled maintenance, construction, etc.) and managing unplanned outages (i.e., responding to unplanned power loss due to fallen trees, storms, etc.) The most frequently conducted and critical subtasks in these areas were defined to be 1) contingency mitigation, 2) writing and checking switching, and 3) conducting switching. Within contingency mitigation, operators compare data from multiple software tools to analyze and validate the likelihood that a specific system will lose power, or "trip", then create a contingency plan to mitigate potential power loss. Regarding writing and checking switching, operators first receive requests for planned outages, or notifications of unplanned outages, from the field. Operators then gather information from a variety of software tools and write the switching order, which becomes the procedure they must follow to successfully deactivate the electricity from an area that will be worked on by field operators. The switching is then checked and verified by another operator. Conducting switching refers to the actual act of executing the switching order and involves collaboration between the grid operator and field operator.

Through further questionnaires and SME interviews, the use case of writing switching was selected. Switching is a fundamental concept that grid operators must be knowledgeable in to be able to conduct their daily tasks successfully and safely. Writing switching is the foundation needed to complete many of these tasks; if an operator can successfully write a switching order, they are more likely to accurately check a switching order, and therefore more likely to successfully conduct the switching (which involves following the written switching order). Therefore, it is necessary to know how to use the switching tools, where to find relevant information, and how to build a switching order.

Furthermore, it is essential that grid operators can do these tasks quickly and accurately. These factors make the writing switching use case a valuable first implementation for AMPed.

Task Analysis & Requirements

Writing switching primarily requires cognitive and psychomotor skills. To write switching, grid operators must utilize up to six different software tools (e.g., EMS and Transmission Asset Mapping Interface [TAMI]) to find relevant information (e.g., clearance points, breaker device numbers). They must find, read, and interpret complex diagrams and documentation, then coalesce this information into a logical sequence of operating devices within their capabilities that can properly energize or deenergize the equipment (i.e., cause or reverse an outage).

Key knowledge relevant to writing switching includes understanding how to read and interpret documentation such as the outage request, electrical schematics, and equipment diagrams. Some of the skills necessary for writing switching are analytical skills, effective scanning of displays, and the ability to plan work and multitask. Currently, writing switching is trained via instructor-led courses, simulations, and OJT. Common mistakes during writing switching include not ensuring adequate boundaries, not considering topology changes, and not considering system changes.

Therefore, an effective training solution for writing switching should meet the following requirements:

1. Facilitate identification and familiarization with multiple software tools
2. Encourage accurate understanding of documentation and diagrams
3. Enable demonstration and practice of logical sequencing
4. Improve a trainee's ability to interpret and draw conclusions from diagrams and documentation
5. Measure and improve acquisition of analytical skills

Implementation

In the employed pedagogy, five proficiency levels are available: novice, advanced beginner, competent, proficient, and expert (Stanney et al., 2021). For the purposes of developing training appropriate to the level of skill of grid operators, these can be mapped to the phases of training. For example, trainees in phase one likely fit most readily into the novice level, while trainees in phase three likely fit most readily into the competent level. To display how AR training can be customized to different proficiency levels, a training scenario for writing switching was implemented at both the novice (i.e., trainees in phase one) and competent (i.e., trainees in phase three) levels. Notably, trainees within the novice or competent state will not have progressed to OJT. Therefore, training scenarios for these levels will not focus on lessening strain on experts during OJT. Additionally, the use case of writing switching primarily requires cognitive and psychomotor skills rather than affective skills, as little interpersonal collaboration is necessary for the task of writing switching. Therefore, the benefits of implementing AMPed within these levels focus primarily on matching the training environment to the real environment to support situated learning and the introduction of stressors when relevant.

For both scenarios, six to eight steps walked the trainees through how to prepare to write switching by gathering relevant information from disparate software tools. These were designed to be conducted in a workstation environment mimicking those in the control room – a desk affixed with multiple computer monitors. The training scenarios proceeded in a stepwise fashion, with digital elements affixed to the trainee's physical environment (e.g., digital information overlaid or tied to their monitors and/or desk). Each step provided new detail about a portion of the switching writing process, either through instruction or formative evaluation. Notably, audio instruction and voice commands were leveraged throughout the scenario, allowing the trainee to focus on their physical environment and receive instruction primarily auditorily and visually when appropriate. The software was developed using Unity game engine and an existing modular architecture for immersive scenario design.

At the novice level, trainees are assumed to have completed phase one of training. This means they have received primarily instructor-led classroom training focused on obtaining their certifications and learning the basics of power distribution components. As such, the AR-based training scenario for novices supported enhanced familiarization with writing switching. Through contextualized instruction, descriptions, activities, and formative evaluations affixed to the trainee's environment, the novice scenario familiarized trainees with software tools relevant for writing switching. Logical sequencing of writing switching was demonstrated through worked examples. Formative evaluations tailored to the expected level of understanding of a novice measured the improvement of analytical skills. Extraneous stressors were not introduced at the novice level, as inherent complexity in retaining the presented information introduces stress to those without existing mental models. Complexity of the scenario was low, as no abstraction of concepts or advanced decision-making was introduced. Assistance within the scenario was high – immediate and elaborative feedback was provided to the trainee. For both errors and correct responses, trainees were given feedback to reinforce understanding. The scenario contained mostly passive elements, as lower fidelity interaction is more appropriate for novice trainees.

At the competent level, trainees are assumed to have completed phase two of training and initiated phase three. At this point, trainees should be familiar with writing switching and have practiced more advanced methods. They likely have had some time in the simulator environment and have spent significant time with the software tools necessary for writing switching. They may have completed some job shadowing, although OJT has not yet begun. The competent training scenario focused on formative evaluations for cognitive and psychomotor skills by adding complexity appropriate to the competent proficiency level. The goal of this scenario was to determine if the trainee has the ability to identify and understand the contents of their available tools for writing switching. These formative evaluations determined the competent trainee's ability to interpret the contents of the documentation and diagrams and demonstrate their ability to create a logical switching sequence. Minimal instruction and descriptions were provided, except upon errors in formative evaluations, congruent with the expected proficiency level of a competent trainee. High-fidelity stressors were sparingly implemented to replicate the real environment; audio stressors mimicked the noise level in the control room and time limits were imposed on environment-contextualized formative evaluations. The scenario had moderate complexity, as low-level abstract elements were introduced (e.g., predicting the outcome of skipping a step and evaluating the consequences) yet formative evaluations remained concrete. Moderate to low assistance was provided; trainees were provided the opportunity to try again when making an error and feedback was provided for those errors, but correct answers received no elaborative feedback. The fidelity of the competent scenario was moderate to high; contextualization was heavily emphasized with realistic renderings of the software tools and interaction activities replicating psychomotor actions.

Once the initial solution was implemented, preliminary user testing was conducted. Six representative end users possessing a background in Transmission Operations were shown the AR training scenarios virtually via Microsoft Teams. One user stated, "It's better than our current remote training," while another mentioned, "This will do a good job at getting your feet wet." These comments indicate the solution can assist novice operators in gaining a better understanding of what their job entails especially in a remote training environment. The end users also identified areas for improvement within the system as conceptualized at the time of testing. Suggestions included refinement of the question-based formative evaluation delivery, increasing intuitiveness of voice commands, and ensuring high quality of digital assets. Four of the six users responded to a survey that included the System Usability Scale (SUS), and responses placed the system at 78.75, which can be interpreted as good, approaching excellent, usability.

By implementing an AR training solution to the writing switching use case, the training environment more closely represented the real environment as relevant stressors were implemented. Beyond this, additional contextualization was added to training content; rather than a slide show or classroom-based instruction on tools, procedures, and systems, instruction and descriptions were directly overlaid on real monitor stations. This allowed trainees to access realistic workstations without physical modification, as digital augmentations enhanced environmental realism and added training and instructional information. Additionally, the audio narration component of the training allowed trainees to have another modality of information intake, ensuring their visual attention could focus on their actual systems while audio cues could enhance learning.

CONCLUSION AND RECOMMENDATIONS

As grid operations modernize and senior workers retire, new grid operators need modern learning approaches. XR, and in particular, AR, has the potential to provide value in this space, as it can help trainees retain information and build skills. While current training for grid workers is extensive, it needs to improve in the ability to 1) match the training environment to the operational environment through methods such as increased contextualization, 2) introduce relevant stressors, 3) train affective skills, and 4) reduce strain on experts during OJT. The introduction of AR within grid worker training has the potential to improve immersion and realism of trainees' environments, add high-fidelity stressors to ensure trainee preparedness, and ultimately ensure new grid operators have the knowledge, skills, and abilities to succeed. When applying AR to grid worker training, the case study of writing switching highlights the ability of AR to heighten contextualization and modernize instruction.

To expand this work, the authors recommend development of training scenarios for additional proficiency levels, beyond novice and competent (i.e., advanced beginner, proficient, and expert). This will show the extensibility of XR to introduce increased stressors and support OJT, as both components become relevant at the proficient and expert levels. Additionally, evaluations of usability, adoptability, and training gains should be conducted to quantify the value and success of AR grid operator training. This type of training can also be expanded to additional use cases within the grid operator space, specifically those which require affective skills. Conducting switching may be a useful candidate for affective training implementation, as execution of this task involves collaboration between operators and field technicians. The energy grid and DOE are poised to benefit from the modernization of training through the introduction of XR technologies and the herein described conceptualization marks a step toward that goal.

ACKNOWLEDGEMENTS

The work described in this paper was funded by the DOE's Office of Science (Contract #: DE-SC0021711). The authors would like to thank and acknowledge EPRI and FirstEnergy for provisioning access to training documentation and subject matter experts, who were instrumental in providing insight via interviews and solution review.

REFERENCES

Billinghurst, M., Clark, A., & Lee, G. (2015). A survey of Augmented Reality. *Foundations and Trends® in Human–Computer Interaction, 8*(2-3), 73–272. https://doi.org/10.1561/1100000049

Butt, O.M., Zulqarnain, M., & Butt, T.M. (2021). Recent advancement in smart grid technology: Future prospects in the electrical power network. *Ain Shams Engineering Journal, 12*(1) 687-695. https://doi.org/10.1016/j.asej.2020.05.004

Chatzopoulos, D., Bermejo, C., Huang, Z., & Hui, P. (2017). Mobile augmented reality survey: From where we are to where we go. *IEEE Access, 5*, 6917–6950. https://doi.org/10.1109/access.2017.2698164

Checa, D., Gatto, C., Cisternino, D., De Paolis, L. T., & Bustillo, A. (2020). A framework for educational and training immersive virtual reality experiences. *Lecture Notes in Computer Science*, 220–228. https://doi.org/10.1007/978-3-030-58468-9_17

Claypoole, V. L., Stanney, K. M., Padron, C. K., & Perez, R. (2020). Enhancing Naval Enterprise Readiness through Augmented Reality Knowledge Extraction. *In Proceedings of the Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*.

Claypoole, V. L., Padron, C. K., Sanchez, S. A., Hodges, C. A., Stanney, K. M., & Perez, R. (2020). Leveraging Emerging Technologies for Shipboard Training and Sailor Support: Recent Advancements and Current Operational Challenges. *In Proceedings of Fleet Maintenance and Modernization Symposium*.

Claypoole, V.L., Horner, C., Sanchez, S.A. (2021). Augmented Reality Training Technologies for Naval Readiness: A Comparison of Shipboard and Pier Side Applications. *In Proceedings of Fleet Maintenance and Modernization Symposium*.

Ćosić, K., Popović, S., Horvat, M., Kukolja, D., Dropuljić, B. (2011). Virtual reality adaptive stimulation in stress resistance training. *Proceedings of 2011 Mental Health and Well-Being across the Military Spectrum.*

Department of Energy (DOE). (2020). Grid Modernization Updated GMI Strategy 2020. Retrieved February 7, 2022, from https://www.energy.gov/sites/default/files/2021/02/f82/GMI_Strategy_FINAL%20as%20of%201.20.21.pdf

Department of Energy (DOE). (2016). The future arrives for five clean energy technologies. Retrieved February 7, 2022, from https://www.energy.gov/sites/default/files/2016/09/f33/Revolutiona%CC%82%E2%82%ACNow%202016%20Report_2.pdf

Hatfield, N., Padron, C.K., Skinner, A., Fidopiastis, C., and Stanney, K. (2019). Augmented Reality for Training and Operational Support Solutions. *In Proceedings of MODSIM World 2019*.

Kaplan, A. D., Cruit, J., Endsley, M., Beers, S. M., Sawyer, B. D., & Hancock, P. A. (2020). The effects of virtual reality, augmented reality, and mixed reality as training enhancement methods: A meta-analysis. *Human*

Factors: The Journal of the Human Factors and Ergonomics Society, *63*(4), 706–726. https://doi.org/10.1177/0018720820904229

Khademi, M., Hondori, H. M., Dodakian, L., Cramer, S., & Lopes, C. V. (2013). Comparing "pick and place" task in spatial augmented reality versus non-immersive virtual reality for rehabilitation setting. *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC).* https://doi.org/10.1109/embc.2013.6610575

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems, 77*(12), 1321-1329.

Moen, P., Kojola, E., & Schaefers, K. (2017). Organizational Change Around an Older Workforce. *The Gerontologist*, *57*(5), 847–856. https://doi.org/10.1093/geront/gnw048

North American Electric Reliability Corporation (NERC). (2022). *System Operator Certification & Credential Maintenance Program*. Retrieved February 7, 2022, from https://www.nerc.com/pa/Train/SysOpCert/Pages/default.aspx

PJM. (2022). *PJM Certification*. Retrieved February 7, 2022, from https://www.pjm.com/training/certification

Punia, B. K., & Kant, S. (2013). A review of factors affecting training effectiveness vis-a-vis managerial implications and future research directions. *International Journal of Advanced Research in Management and Social Sciences, 2*(1), 151-164.

Riley J.M., Flint J.D., Wilson D.P., Fidopiastis C.M., & Stanney K.M. (2020) Towards a Predictive Framework for AR Receptivity. *Virtual, Augmented and Mixed Reality. Design and Interaction*, 135-151. https://doi.org/10.1007/978-3-030-49695-1_10

Stanney, K. M., Archer, J. A., Skinner, A., Horner, C., Hughes, C., Brawand, N. P., Martin, E., Sanchez, S., Moralez, L., Fidopiastis, C. M., & Perez, R. S. (2021). Performance gains from adaptive extended reality training fueled by Artificial Intelligence. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, *[Special Issue Article]* 1-24. https://doi.org/10.1177/15485129211064809

Viglialoro, R. M., Condino, S., Turini, G., Carbone, M., Ferrari, V., & Gesi, M. (2021). Augmented reality, mixed reality, and hybrid approach in Healthcare Simulation: A Systematic Review. *Applied Sciences, 11*(5), 2338. https://doi.org/10.3390/app11052338

Zhou, K., & Yang, S. (2018). 5.11 Smart Energy Management. In *Comprehensive Energy Systems, 5*, 423–456. https://doi.org/10.1016/B978-0-12-809597-3.00525-3